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APPLICATION OF THE ITERATIVE BEAM PROCESSOR TO LONG-PERIOD RAYLEIGH WAVES

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7 OCTOBER 1975

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The technique was applied to superposed recordings of Rayleigh waves at LASA. It was found that multipathing of Rayleigh waves can cause enough leakage

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APPLICATION OF THE ITERATIVE BEAM PROCESSOR TO LONG PERIOD RAYLEIGH WAVES

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ABSTRACT

The effectiveness of the iterative beaming technique for the separation of superposed Rayleigh wave signals was evaluated. This technique can be useful for the detection and discrimination of seismic events the signals of which arrive simultaneously at a seismic array.

The technique was applied to superposed recordings of Rayleigh waves at LASA. It was found that multipathing of Rayleigh waves can cause enough leakage into the beam of the desired event to make the separation impossible if the amplitude of waves from the event to be eliminated is more than three times that of the event of interest.

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INTRODUCTION

It has been shown theoretically that the iterative beam processor is equivalent to the maximum likelihood processor (Blandford et al., 1973; Shumway, 1972; Dean et al., 1968). The method has been successfully demonstrated on short period body wave data at TFO and was shown to be superior to simple beaming. This report evaluates the performance of the method when it is applied to mixed surface waves.

The iterative beam processor assumes that the directions of the two sources are known. By beaming the array at the first epicenter one obtains a first signal estimate for the first event (which is contaminated by the second event). The time shifted first signal estimate is then subtracted from all sensor traces and the resulting traces are beamed on the second event to obtain first estimate of the second signal. This estimate is also subtracted from the original traces and the result is rebeamed on the first event to obtain a second estimate for the first signal. Repetition of this procedure should theoretically yield maximum likelihood estimates for the two signals (Blandford et al., 1973). The computation involves only time shifting and summing instead of the complicated matrix operations and convolutions needed in computing maximum likelihood filters the usual way. If the directions of the two (or more) signal arrivals are not known the iterative beaming method cannot be used.

Although the method can be applied to long period body waves, long period surface waves are more important in discrimination studies and we shall apply the method to superpositions of Rayleigh waves. The method was shown to be theoretically effective for superposed plane waves, but it has to be tested

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Blandford, R. R., Cohen, T. J., and Woods, J. W., 1973. An iterative approximation to the mixed signal processor, Seismic Data Analysis Center TR-73-7, Teledyne Geotech, Alexandria, Virginia.

Shumway, R. H., 1972. Some applications of a mixed signal processor, Seismic Data Laboratory Report #280, Teledyne Geotech, Alexandria, Virginia.

Dean, W. C., Shumway, R. H., and Duris, C. S., 1968. Best linear unbiased estimation for miltivariate stationary processes, Seismic Data Laboratory Report #207, Teledyne Geotech, Alexandria, Virginia.

on actual surface wave data since surface waves are commonly refracted laterally, resulting in multipathing and deviations of the directions of approach of the signal from the great circle path.

The usefulness of the method will be limited by these properties of surface waves, and the extent of these limitations should be determined empirically. The amount of energy leaking into the iterative beams in the directions other than the epicentral direction impairs the detectability of surface waves from weak events in the presence of a large event. Since the surface wave magnitude is an important discriminant these limitations must be known. The method is also suitable, as shown below, to quickly separate multipath arrivals in the time domain and can be used as an effective research tool for the understanding of multipathing in specific cases.

DATA

A set of events which was previously used in a study of frequency wavenumber spectra (Lambert and Der, 1974) was utilized in this report. The epicentral data of these events are given in Table I. Vertical component long period seismometer recordings at LASA were used in this study. Both the full array and a part of the full array consisting of the center element A_o and the B and C rings was used in the analysis. Two elements of C rings (C1 and C2) were omitted due to data problems. In addition, the element D was omitted for the Argentina event for the same reason. In addition to individual event recordings, linear combinations of seismic traces from several events and noise were also analyzed. The same combinations were used in a previous study (Lambert and Der, 1974).

Lambert, J. and Der, Z. A., 1974. Comparison of two segment maximum likelihood (TSML) frequency wavenumber spectra with the fast beamed frequency wavenumber spectra (FKPLOT), Seismic Data Analysis Center TR-74-6, Teledyne Geotech, Alexandria, Virginia.

TABLE 1

Epicentral Data

	Region	Date	Origin Time*	Location*		Depth km	From LASA Dist. km	From LASA Azimuth degrees	m_b	M_s
Event 1	Phillipine Islands Region	8 Jan 72	05:27:53	20.9N	120.2E	33	11155	316.5	6.2	6.3
Event 2	New Britain Region	28 Jul 71	01:10:24	5.1S	152.9E	33	11229	274.4	6.0	6.4
Event 3	New Hebrides Islands	24 Jan 72	03:55:42	13.0S	166.4E	28	10839	259.1	5.6	6.2
Event 4	Baja California	14 Apr 71	11:38:42	27.7N	112.4W	33	2176	196.5	5.4	5.2
Event 5	San Juan Province, Argentina	26 Sep 72	21:05:44	30.9S	68.1W	16	9421	147.9	5.9	5.8
Event 6	Guatemala	22 Jan 72	13:08:50	14.0N	91.0W	102	3895	153.7	5.5	-

* Values for origin time are rounded to nearest second and locations' values are rounded to nearest tenth of a degree.

DATA PROCESSING

Recordings of individual events were processed by the iterative beaming technique by assuming various directions for a second (absent) signal and examining the leakage of the energy from the event into the iterative beam. Iteration is stopped if the rms difference between successive iterations was less than 2% or if the number of iterations exceeded six. This assumes that the above criteria are sufficient to assure that the theoretical limit of improvement was sufficiently approximated. The ratio of the rms signal relative to the rms iterative leakage beam and the simple leakage beam was plotted on polar diagrams in dB units in order to compare the relative effectiveness of the two processes. The azimuths of the second signal were assumed to be at 30° intervals from the azimuth of the first (single event) signal. Figures 1 through 6 clearly show the superiority of the iterative technique over the simple beam. These diagrams are comparable to the f-k spectra using FKPLOT and the maximum likelihood spectra (Lambert and Der, 1974). It must be pointed out however that the iterative beaming is a wide band process while the f-k spectra were computed for a single frequency. Nevertheless, both kinds of results demonstrate the higher resolution property of the maximum likelihood process. In discussing the results we shall occasionally refer to the f-k spectra given in the previous report (Lambert and Der, 1974) which analyzes the same events.

Combined events were processed to produce signal estimates for both events which can be visually compared to the original signals.

RESULTS

In the following we shall describe the polar plots of energy rejection of simple beams and iterative beams centered at directions other than that of the epicenter for various events. In these plots the direction of epicenter is marked by an arrow. The rejection in this direction is naturally zero. In the other directions spaced at 30° intervals the ratio of the rms amplitudes of the event (averaged over the various sensors) and that of the beam and iterative beam are plotted in decibel units.

Figure 1 shows these plots for the full LASA array obtained for the Baja California event. This event has a short surface wave train not exceeding in duration the window length (256 seconds) used. Figure 7d shows the locations for three overlapping time windows. The middle one includes the full surface wave train, the first one, the first half and the third one, the second half of it. Beams have been computed for three velocities 3.34, 3.56, and 3.79 km/sec. For the first window the best rejection is obtained at the two higher velocities, for the second and third at the two lower velocities. This undoubtedly reflects the dispersion of surface waves, the longer period waves at the beginning of the wavetrain having a higher phase velocity. The velocity 3.56 km/sec seems to be a good overall beam velocity in this case and it was used exclusively for time domain analysis of signals presented in the latter part of this document.

Figure 2 shows the results for the reduced array containing only the A, B, and C rings (as described above). The dependence of the results on the beam velocities and the position of the window is about the same as in the previous case. Note the additional rejection of off beam energy by the iterative process, when compared to the simple beam. An explanation for this is that the first beam due to the small array is a poor approximation to the signal waveform which improves greatly as the iteration proceeds. Moreover, lateral inhomogeneities effect the wave shapes less within the smaller array and the wave appears to be more coherent. Since iterative beaming (or its equivalent the maximum likelihood filtering) is critically dependent on the assumed signal model, which is a coherent plane wave, this process will be

markedly more efficient using the smaller array. The improvement of the iterative technique over the simple beam ranges between 10-15 dB in this case.

Figure 3 shows a similar set of plots for the Argentine event for the full array. The location of the data windows for these diagrams is shown in Figure 7e. These are nonoverlapping windows sampling various parts of the Rayleigh wave train. The performance of the iterative beam relative to the beam is poor in the average. The polar plots for the reduced array show visible improvement relative to the full array beams (Figure 4). The beginning of the wave train yields better results than the succeeding data windows. We assume that multipathing is the cause of these difficulties. The visual similarity of traces is poor and the f-k spectra obtained for this event in a previous study (Lambert and Der, 1974) indicates multipathing. We shall show later that a multipath arrival in the latter part of the wave train can actually be isolated by the iterative beaming technique. This opens up a new application of this technique for studying multipathing. The performance of the process changes less with the beam velocity than in the previous example, possibly because spectral components of varying phase velocities are mixed by multipathing within the same windows.

Figures 5 and 6 show similar polar plots for the Guatemala event. We note essentially the same features, slight dependence on velocity attributable to the varying frequency content of the time windows, superior performance of the iterative processor and the reduced array outperforming the full array. The location of the time windows are shown in Figure 7f. The performance deteriorates with time indicating that the coda consists of multipathed incoherent arrivals.

Separation of Combined Events

Although the previous results show how effective the separation can be in the root mean square sense it is desirable to see how well the waveforms of earthquakes can be separated in the time domain. If the separated waveforms cannot be recognized as a waveform from an earthquake, that is, dispersed surface wave trains, it would be unwise, for instance, to determine surface wave magnitudes from them since they could be multipath arrivals or long

period microseisms. In the following we shall show the separation of superposed pairs of events. The seismograms of the individual events are shown in Figures 7a-7f. The pairs of events were superposed with roughly equal maximum amplitudes, and decomposed by iterative beaming into the individual events. To test for leakage of each event into the iterative beam arrived at the other event the same procedure was performed in the case when only one event was present.

Throughout the following computations the two events were adjusted and their maximum amplitudes within the time interval processed were equal. The results of the computations which followed were plotted on a fixed scale and the amplitudes of the plots are directly comparable. This was done in order to compare the amplitudes of the separated waveforms and the energy leakage.

Figures 8a and b show the results of such analysis for the superposition of the Philippine Islands event with the New Britain event for the full LASA array. The traces on the top of figure 8a show the results for the Philippine event when it was present only. The leakage of energy into the beam of the New Britain event is hardly reduced beyond the first iteration. A similar procedure for the New Britain event as shown on top of figure 8b shows visible reduction of leakage into the beam of the Philippine event (traces 1 vs. 2 on the left) by about a factor of 2 on the second iteration.

The middle traces in Figures 8a and b are biased beams for the individual events. These traces are included for comparison of waveforms. Theoretically their amplitudes are biased, less than the actual amplitudes of the beams on the individual events. The difference is, however, very small only about 5% in the worst case, the full array, as calculated from the bias formula of Blandford, Cohen, and Woods (1973). Since we need only a rough comparison between the amplitudes of the beam and the leaked waveforms we can use these for comparison. Unbiased beams for the same case were not computed since this would have required a separate iteration sequence.

As seen by comparing waveforms, the ratio of the original event amplitudes to that of the leakage into the beam aimed at the other event is about 4:1 for the Philippine event and 7:1 for the New Britain event. These would be roughly the limits imposed by multipathing and the array configuration in the given case in detecting small event hidden in the tail of the dominant event.

Ambient noise, being of very low amplitude, does not influence the results in this case. The bottom traces on Figure 8a and b show the results of the decomposition when both events are present. The successive iterations show essentially the same waveforms indicating that the first beams of the large array achieved a quite efficient separation.

The results of an identical procedure for the reduced LASA array (A, C, and D rings) are shown in Figure 9a and b for the same two events. Because of the smaller size of the array the iteration achieves more improvement relative to the simple beam. Nevertheless, the leakage problem is more severe, the amplitudes (maxima measured) of the original amplitude relative to the leakage is about 2:1 for the Philippine event and a somewhat better 4:1 for the New Britain event. More iterations were also needed to achieve the results although not much change can be seen beyond the third unbiased iteration for any of the events. The bottom traces again show the separation results when both events are present. Since the leakage is still fairly small not much change is seen in the waveforms of successive iterations. The azimuthal separation of the two events in this case was quite good, about 42°, way beyond the resolution capability of the maximum likelihood (iterative beam) process as seen in the report by Lambert and Der, 1974. It seems therefore that the cause of "leakage" is multipathing, real energy coming from the undesired event in the direction of the event to be looked at. This limits the application of this technique to superposed Rayleigh waves, and this limitation will remain until the multipathing phenomenon is better understood and is properly corrected for. Using a larger array reduces leakage due to its higher resolution but does not eliminate it completely.

The following figures show the results of identical procedures applied to other event pairs. Figures 10a and b show the results for the Philippine event as combined with the New Hebrides event when the full LASA array is used. These events are separated in azimuth by 57°. Shortly summarizing the ratio of the original amplitudes to the leakage is about 3:1 for the Philippine event and somewhat better than 2:1 for the New Hebrides event, thus in spite the large azimuthal separation and the full array used the leakage is not negligible. As in the previous case the first beam is quite effective, and no great change in the waveforms can be seen beyond the second

unbiased iteration. It is a little hard to believe that so much energy could be diverted from the main circle path, but in the case of New Hebrides event the later arrival of the leaked energy seems to agree with the notion that it arrived over a longer path.

Figures 11a and b show the results for the reduced array. The ratio of original to leaked wave amplitudes is about 3:1 for the Philippine event and somewhat larger than 2:1 for the New Hebrides event, the same as before. The rest of the remarks above also apply in this case.

The next case shown in Figures 12a and b is the separation of the Baja California and Guatemala events with the full LASA utilized. The angular separation of the azimuths of the epicenters to LASA is about 43°. The ratio of the original trace amplitudes to that of the residual trace is about 4:1 for the Baja event and 4:1 for the Guatemala event. The separation of waveforms is quite good, although some leakage of the Guatemala event into the beam aimed at Baja is evident.

Figures 13a and b show the same two events processed using the reduced LASA array only. The ratio of original and leaked amplitudes is about 5:1 for the Baja event and 4:1 for the Guatemala event. Again more iterations are needed to achieve convergence. On the separated superposed traces energy leaked from the Guatemala event is quite evident.

The results for the event pair Baja California-Argentina earthquakes using the full LASA array are shown in Figures 14a and b. The azimuthal separation of these events is 48° but f-k plots indicate that the Argentine event is considerably multipathed and most of the energy does not come from the actual azimuth of the source (Lambert and Der, 1974). Since the above example was calculated using the actual azimuth along the great circle the results are correspondingly poor. The Argentine event leaks a considerable amount of energy into the beam aimed at Baja California, but the beam aimed at the actual azimuth of this event also contains considerable energy. The separation of events therefore is not successful.

Figures 15a and b show the results for this event pair using the reduced array, leading to similar conclusions as above.

CONCLUSIONS

Although the iterative beaming process has been shown theoretically to be very effective in separating multiple events its application to teleseismic Rayleigh waves is limited by the deviation of these waves from the assumed signal model, the plane wave with a constant phase velocity. Wave dispersion which causes a gradual distortion of the plane waveform across the array does not seem to be a major factor in reducing the effectiveness of this processor even for large arrays (LASA). The main cause of the difficulties seems to be multipathing and deviation from the great circle azimuth due to lateral refraction. The performance of this processor depends on the array configuration and the location of the events to be separated. Nevertheless, the above examples, although limited in number, seem to indicate that, for many cases, the separation cannot be relied on if great circle a-priori azimuths are used and if the amplitude of the larger event is more than three times that of the smaller event. This is also true for measuring a reliable M_s. This agrees well with previous studies of FKCOMB vs. maximum likelihood filtering (Lambert and Der, 1974).

In applying the method it can be assumed that the events in question have been detected on the short period instruments and therefore their great circle azimuths are known and the separation has to be performed in order to measure the excitation of surface waves. It is also possible to estimate the azimuth of the larger event by one of f-k spectra. This might be useful practice. A-priori information about multipathing from the epicenter might also be used. The estimated azimuths, instead of great circle azimuths, could conceivably increase the effectiveness of the separation since the actual directions of energy arrivals could be included in the model. Thus in applying the method several options are available where one can trade computational efficiency and speed for more effective separation. In cases of complicated multipathing it may be impossible to untangle the waves satisfactorily and M_s values may simply have to be made from the f-k spectra.

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Blandford, R. R., Cohen, T. J., and Woods, J. W., 1973. An iterative approximation to the mixed signal processor, Seismic Data Analysis Center TR-73-7, Teledyne Geotech, Alexandria, Virginia.

Dean, W. C., Shumway, R. H., and Duris, C. S., 1968. Best linear unbiased estimation for muitivariate stationary processes, Seismic Data Laboratory Report #207, Teledyne Geotech, Alexandria, Virginia.

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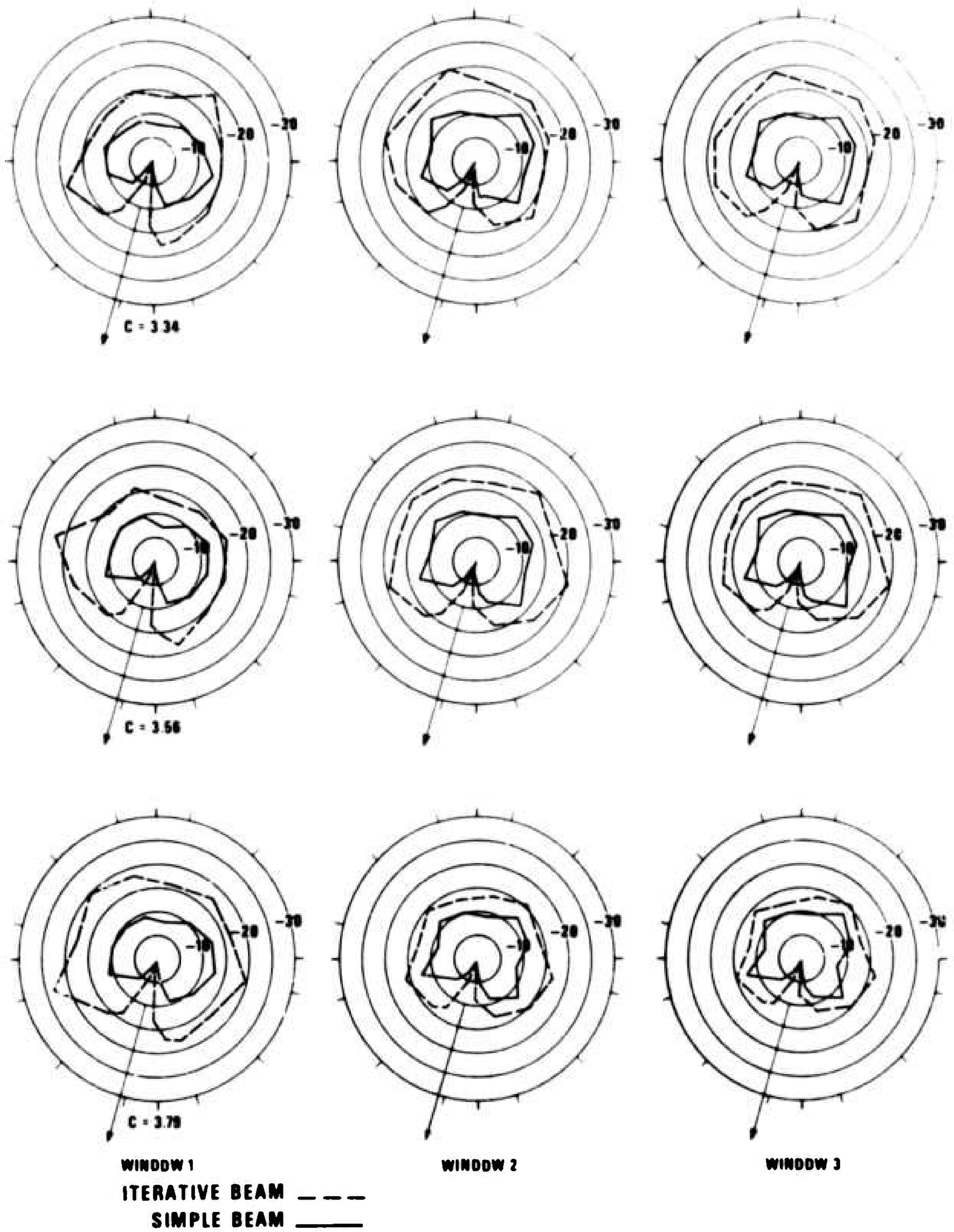

Figure 1. Polar plots of energy rejection in dB for iterative beam vs. simple beam for the Baja California event. Three overlapping data windows and the beam velocities (c) used. All LASA LPZ sensors used.

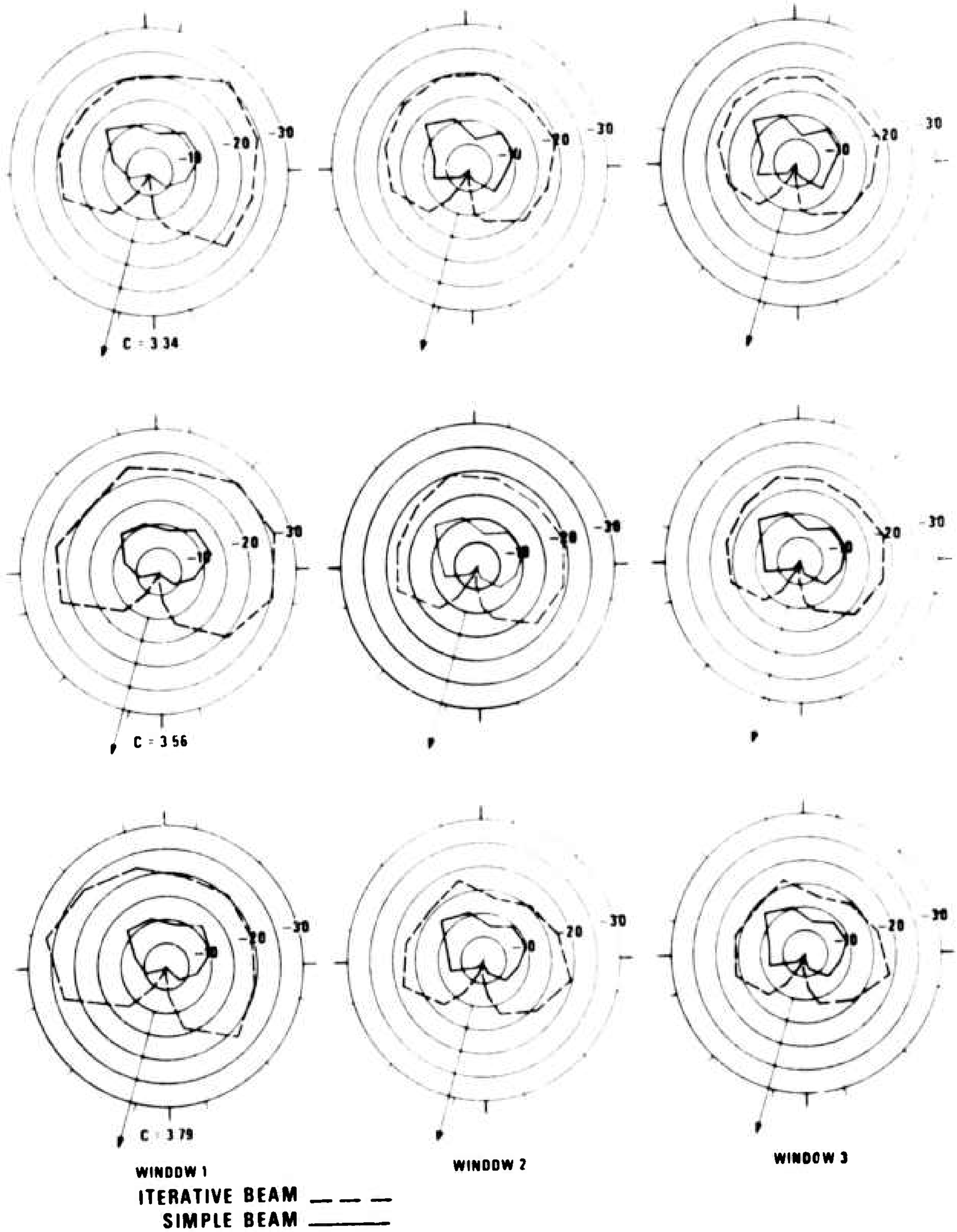

Figure 2. Polar plots of energy rejection in dB for iterative beam vs. simple beam Baja California event. Only the A, B, and C rings of LASA are utilized.

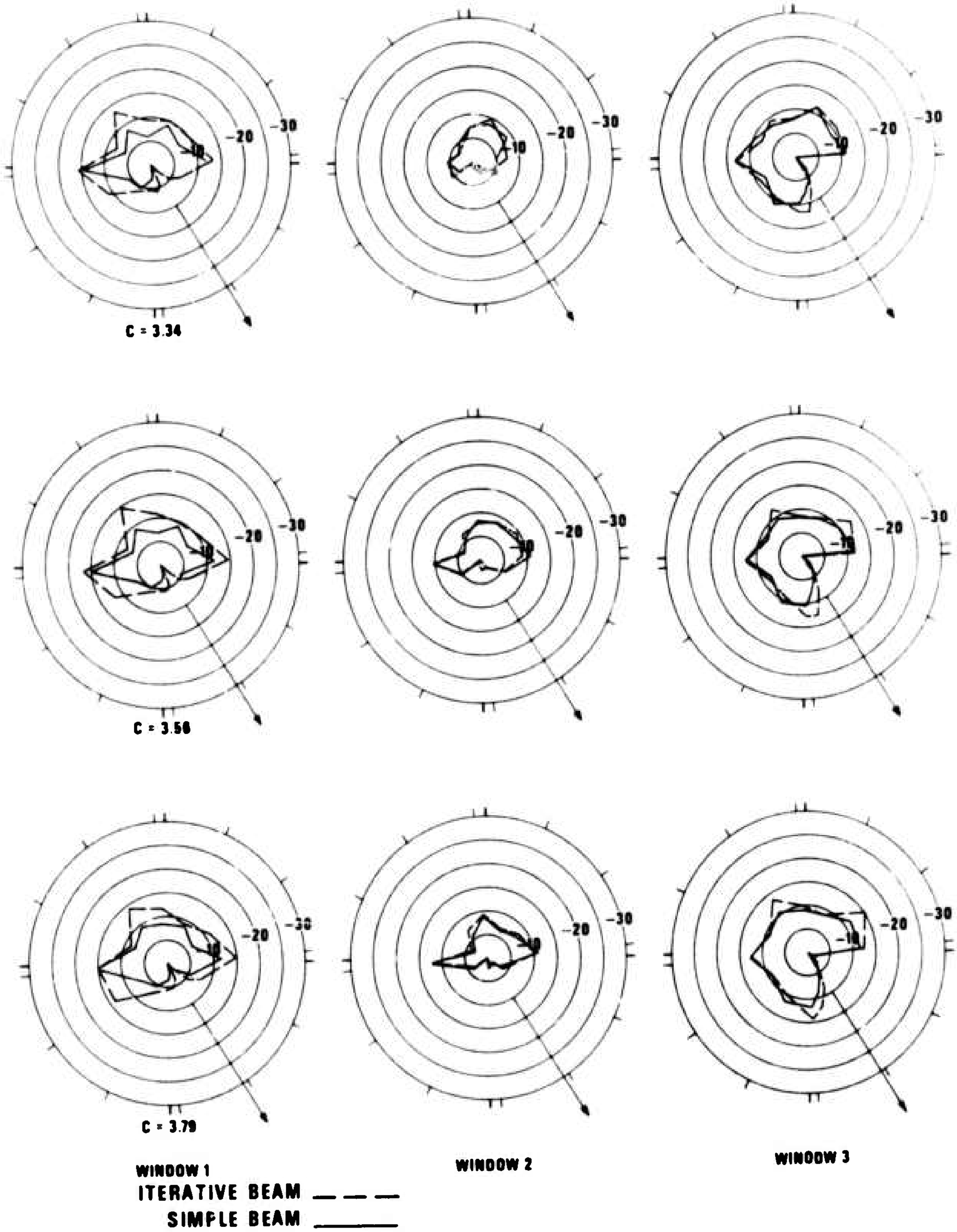

Figure 3. Polar plots of energy rejection in dB for iterative beam vs. simple beam, Argentine event. All LASA LPZ sensors used.

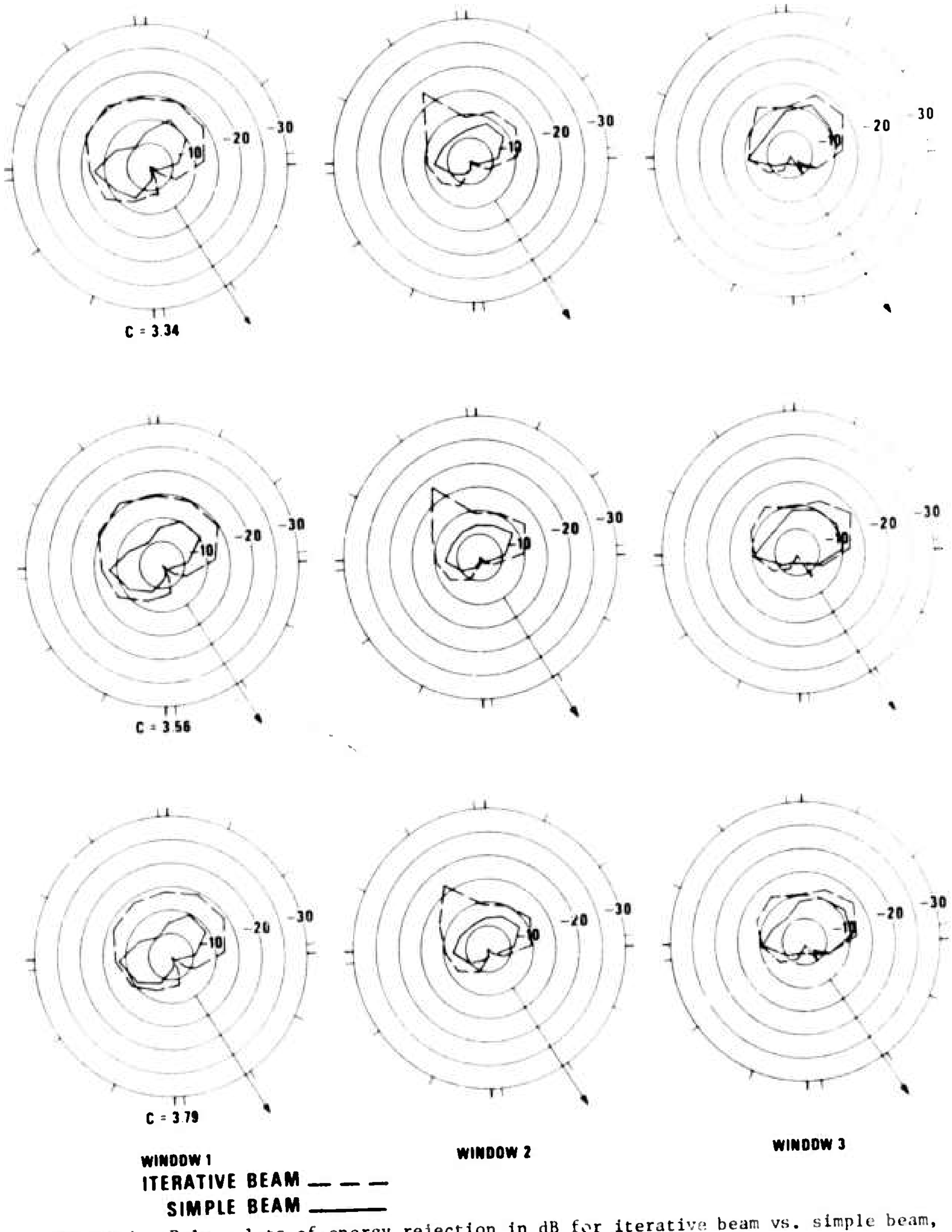

Figure 4. Polar plots of energy rejection in dB for iterative beam vs. simple beam, Argentine event. Only the A, B, and C rings of LASA are utilized.

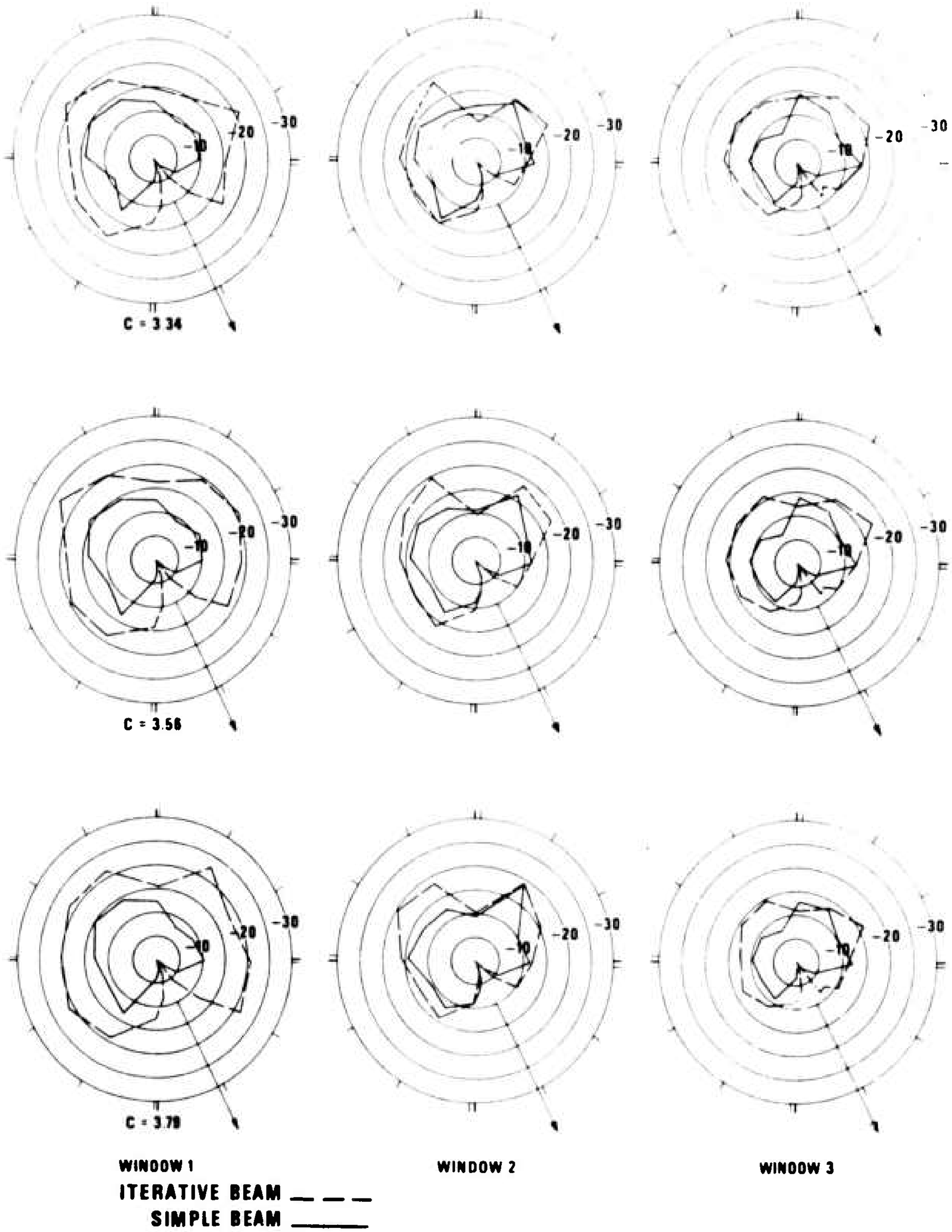

Figure 5. Polar plots of energy rejection in dB for iterative beam vs. simple beam, Guatemala event. All LASA LPZ sensors used.

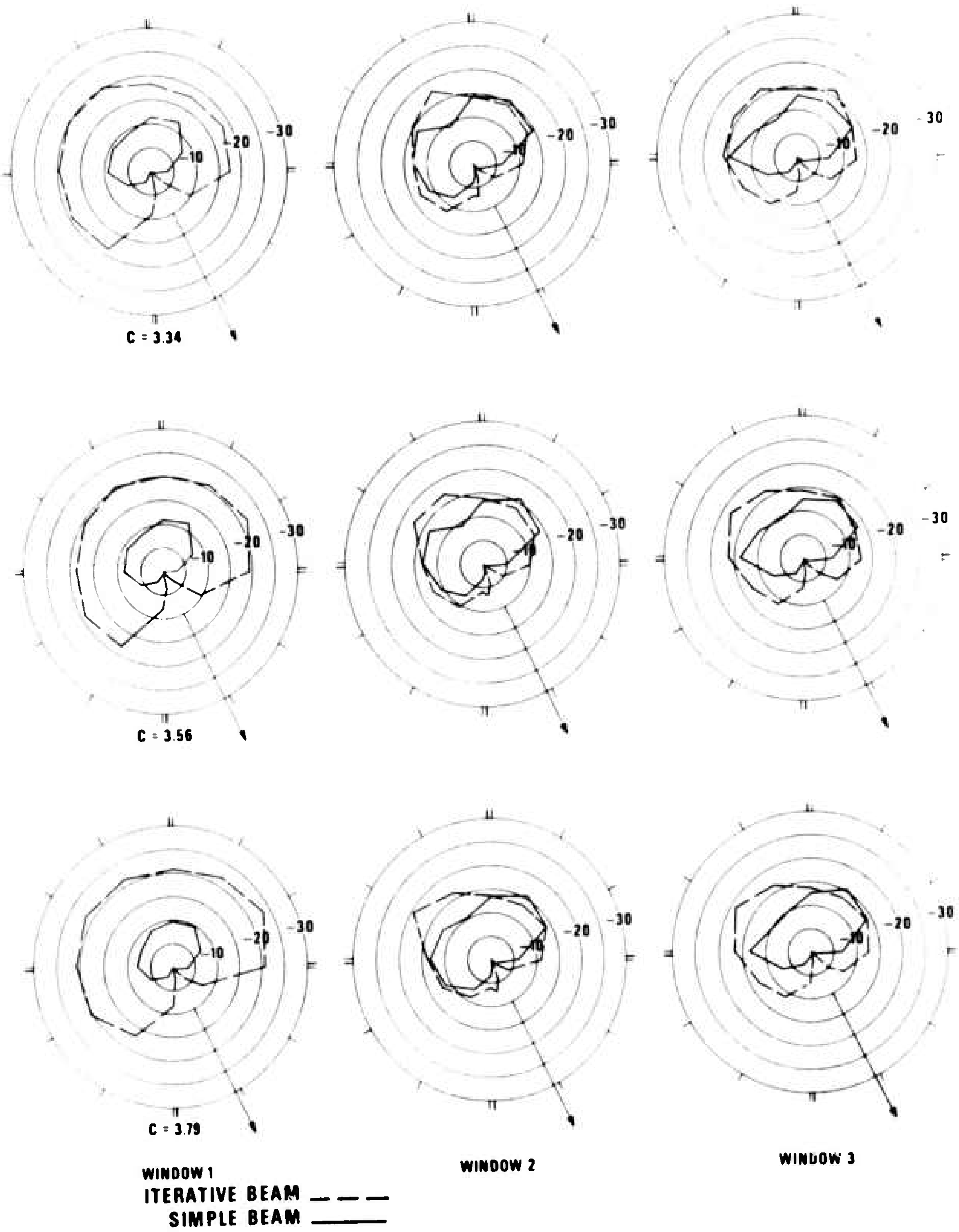

Figure 6. Polar plots of energy rejection in dB for iterative beam vs. simple beam, Guatemala event. Only the A, B, and C rings of LASA are utilized.

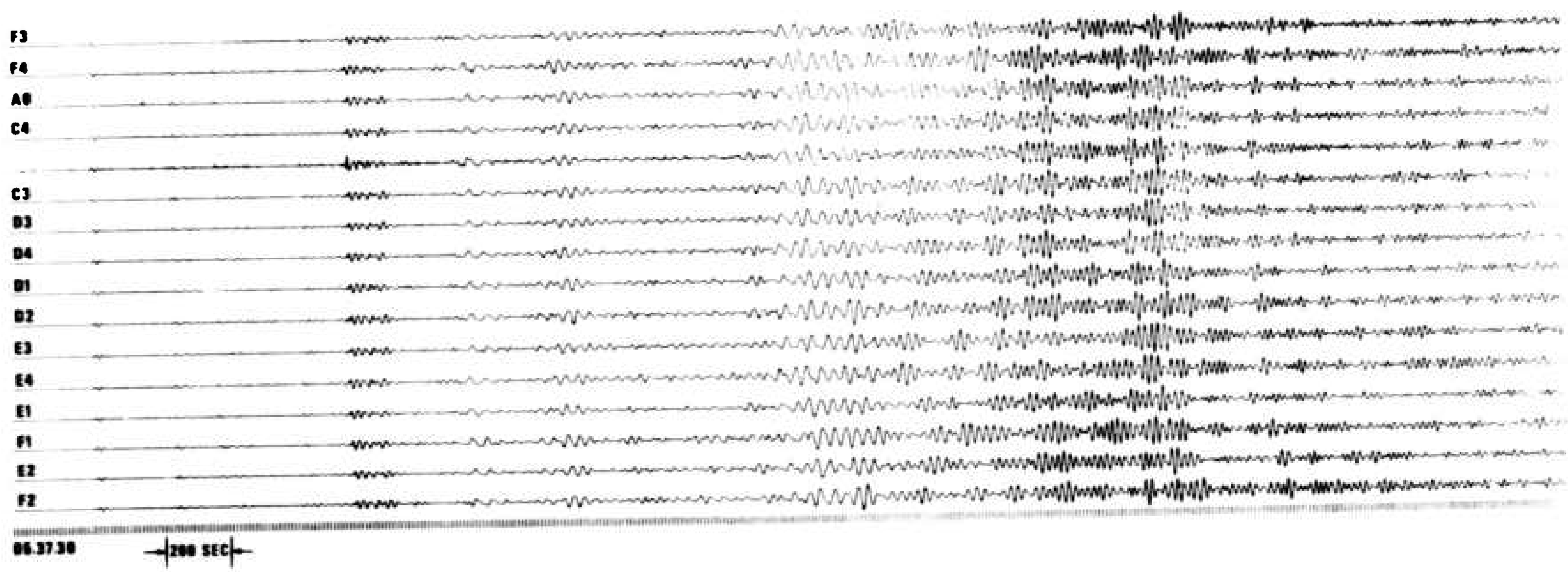

Figure 7a. LASA seismograms of the Philippine Islands Event.

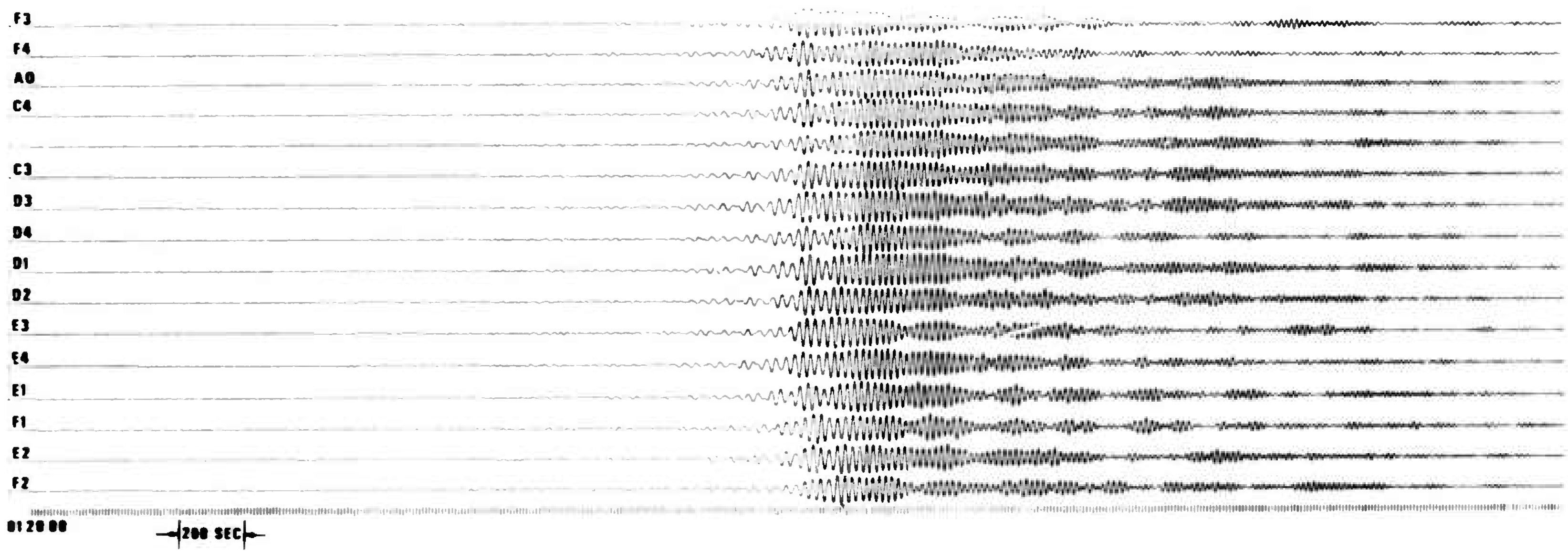

Figure 7b. LASA seismograms of the New Britain event.

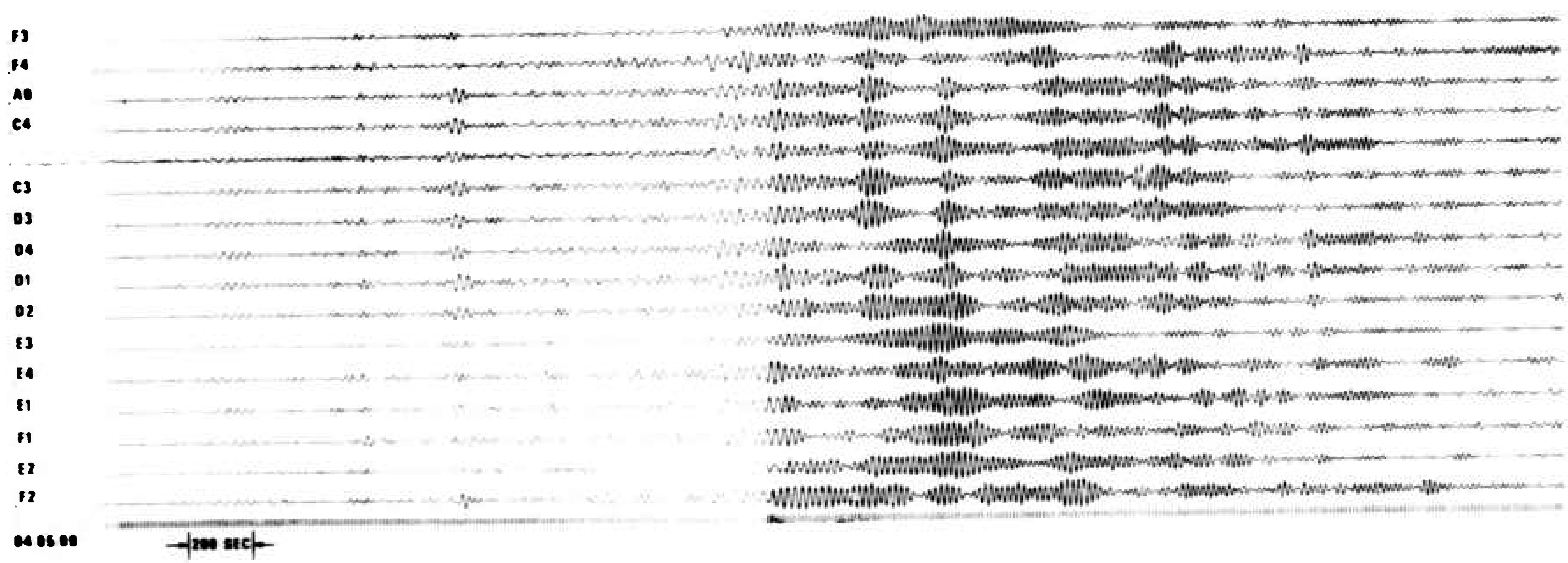

Figure 7c. LASA seismograms of the New Hebrides event.

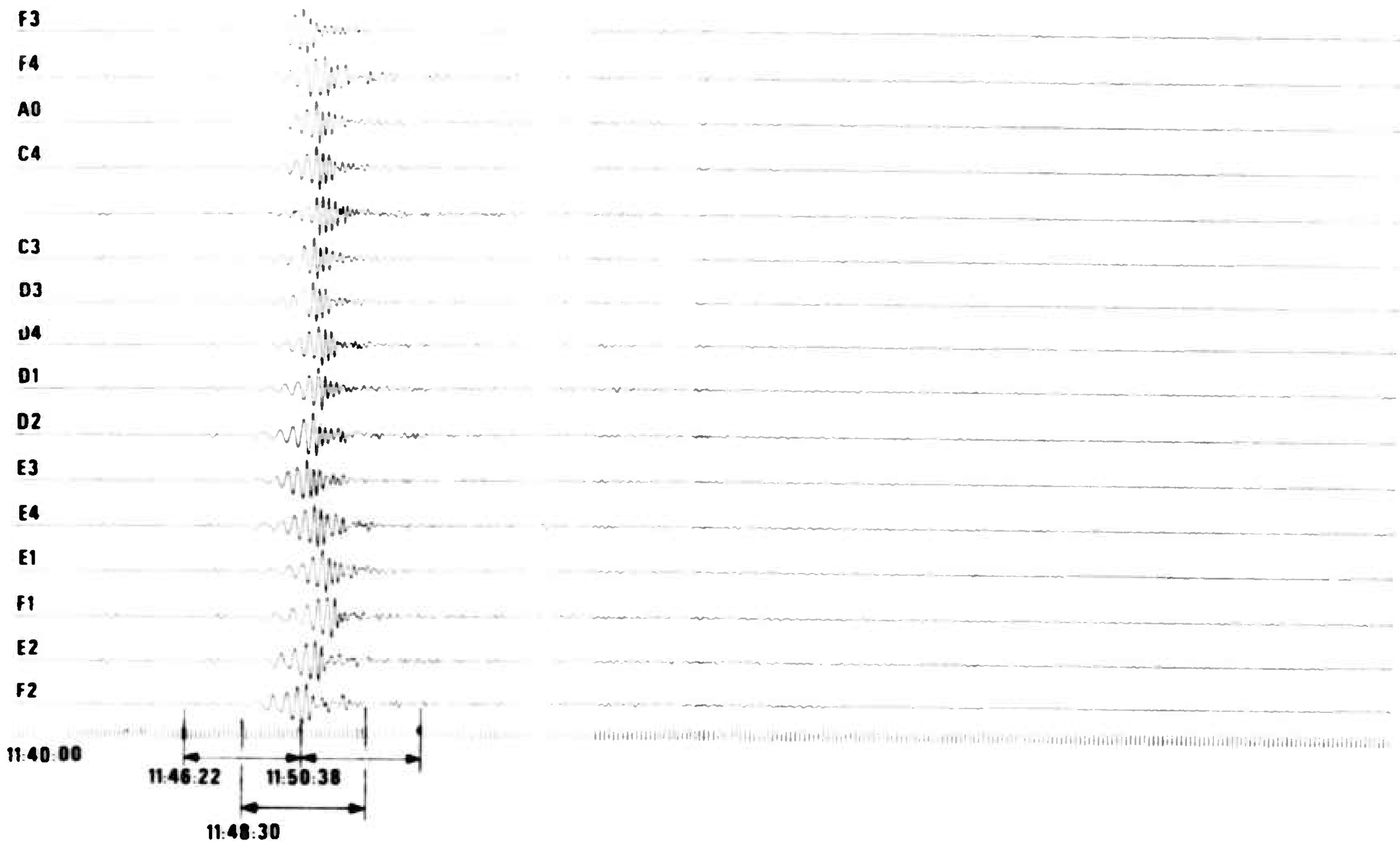

Figure 7d. Location of 256 second overlapping time windows used - Baja California event.

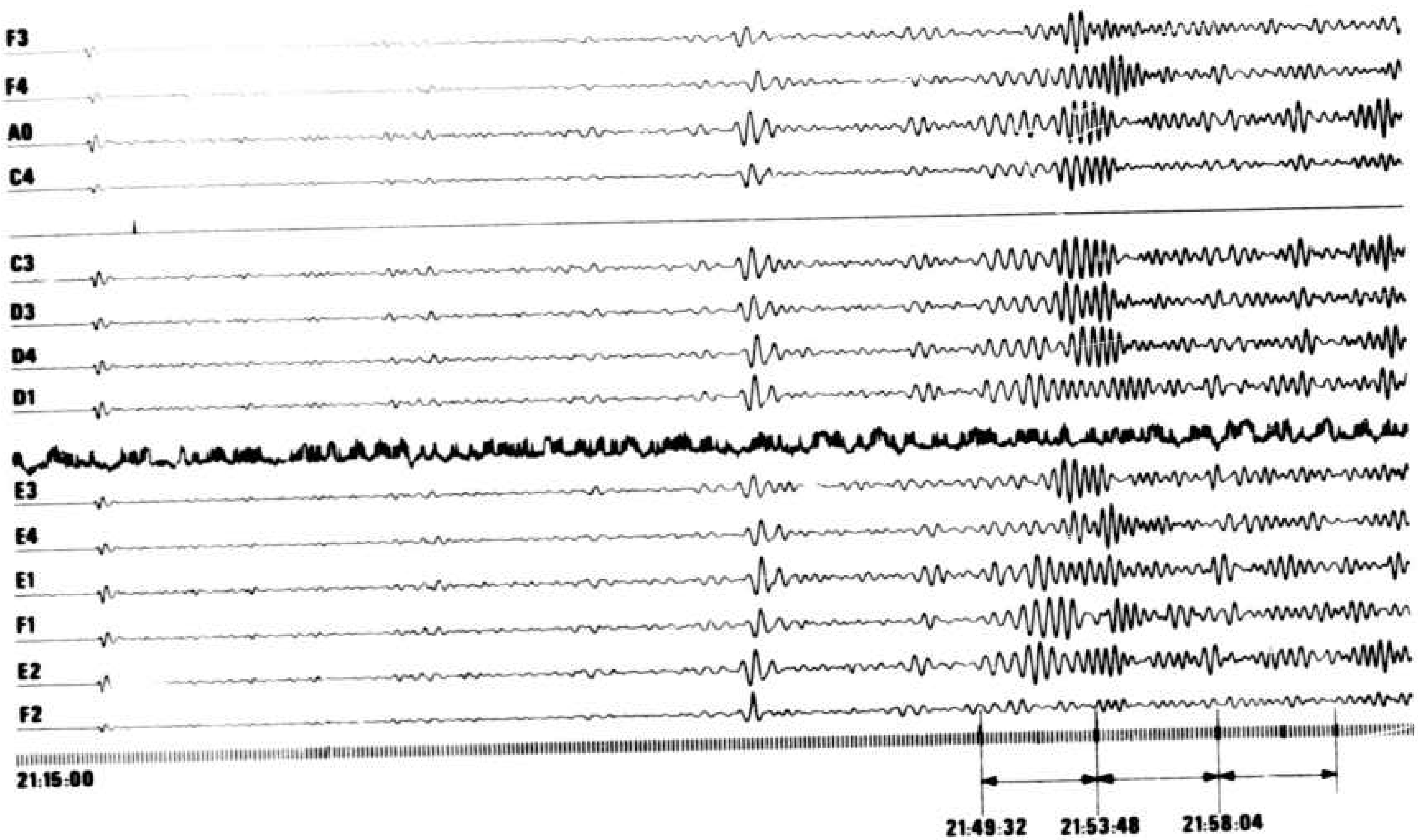

Figure 7e. Location of 256 second nonoverlapping time windows used - San Juan Province Argentine event.

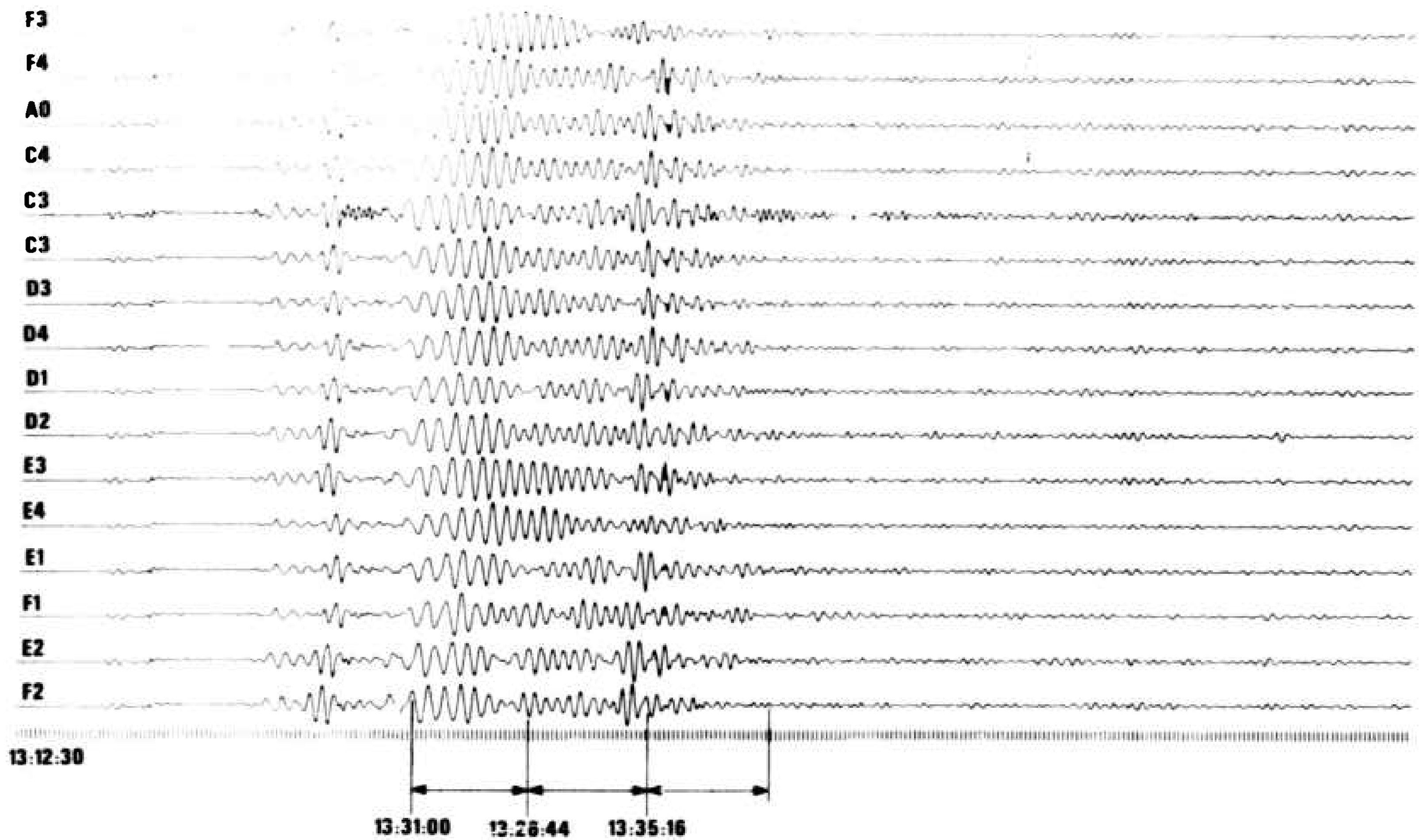

Figure 7f. Location of 256 second nonoverlapping time windows used - Guatemala event.

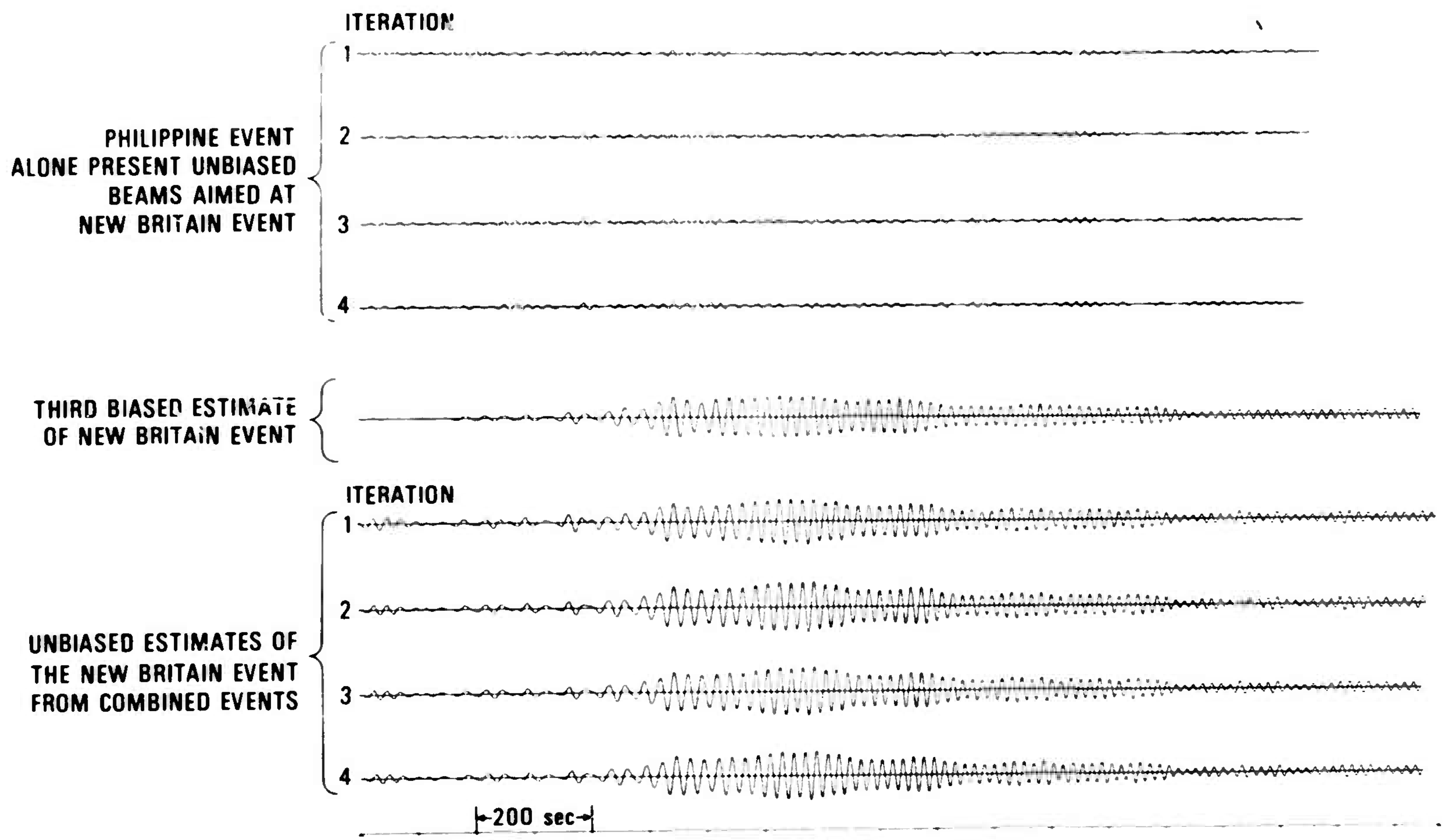

Figure 8a. Time domain analysis of the Philippine and New Britain events using the full LASA array. Top traces show the results of iterative beaming when only one of the above mentioned events is present (Philippine event on 8a, New Britain on 8b). The set of traces below this show the results when only the other event is present (New Britain and Philippine on Figures 8a and 8b respectively). The two sets of traces at the bottom show the decomposition of both events superposed at the approximately equal amplitudes (Philippine event extracted on 8a, New Britain on 8b). All traces in the same set are plotted using the same scale factor in order to make the trace amplitudes comparable. Subsequent figures 9-15 are organized in a similar way, only the events change.

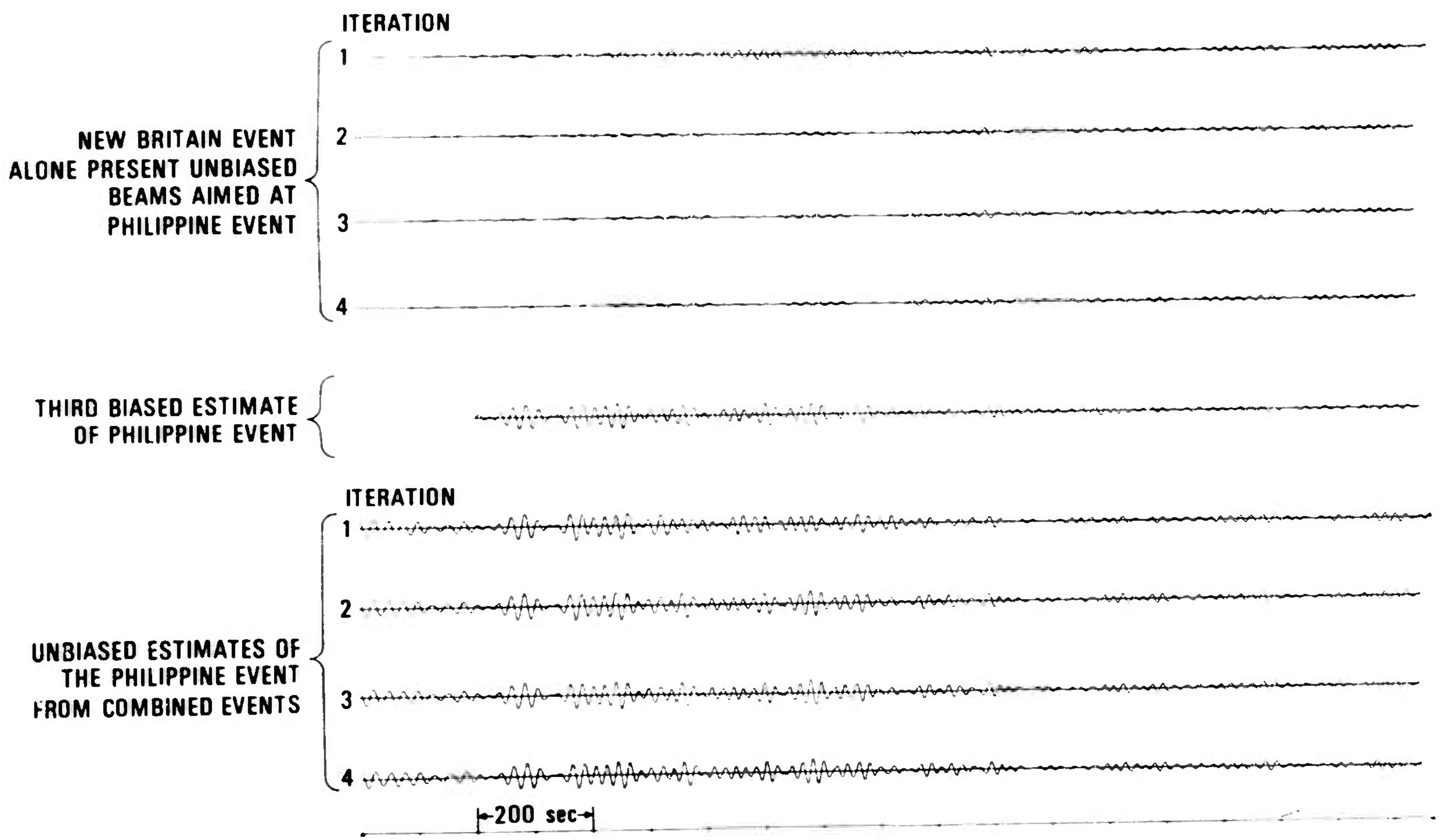

Figure 8b. Time domain analysis of the Philippine and New Britain events using the full LASA array. Top traces show the results of iterative beaming when only one of the above-mentioned events is present. (Philippine event on 8a, New Britain on 8b). The set of traces below this show the results when only the other event is present (New Britain and Philippine on Figures 8a and 8b respectively). The two sets of traces at the bottom show the decomposition of both events superposed at the approximately equal amplitudes (Philippine event extracted on 8a, New Britain on 8b). All traces in the same set are plotted using the same scale factor in order to make the trace amplitudes comparable. Subsequent figures 9-15 are organized in a similar way, only the events change.

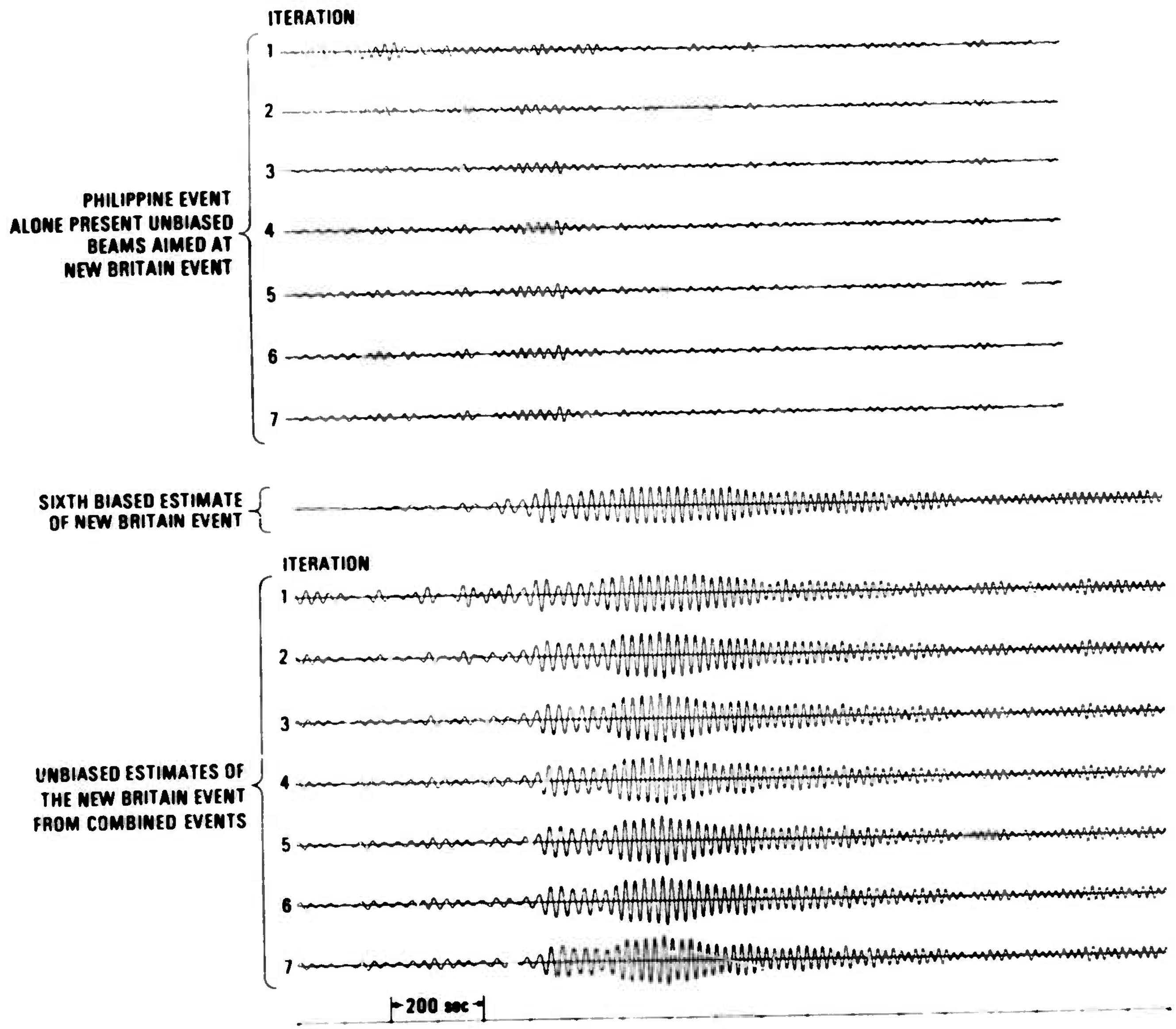

Figure 9a. Time domain analysis of the Philippine and New Britain events using the reduced LASA array. For detailed explanation see caption under Figure 8.

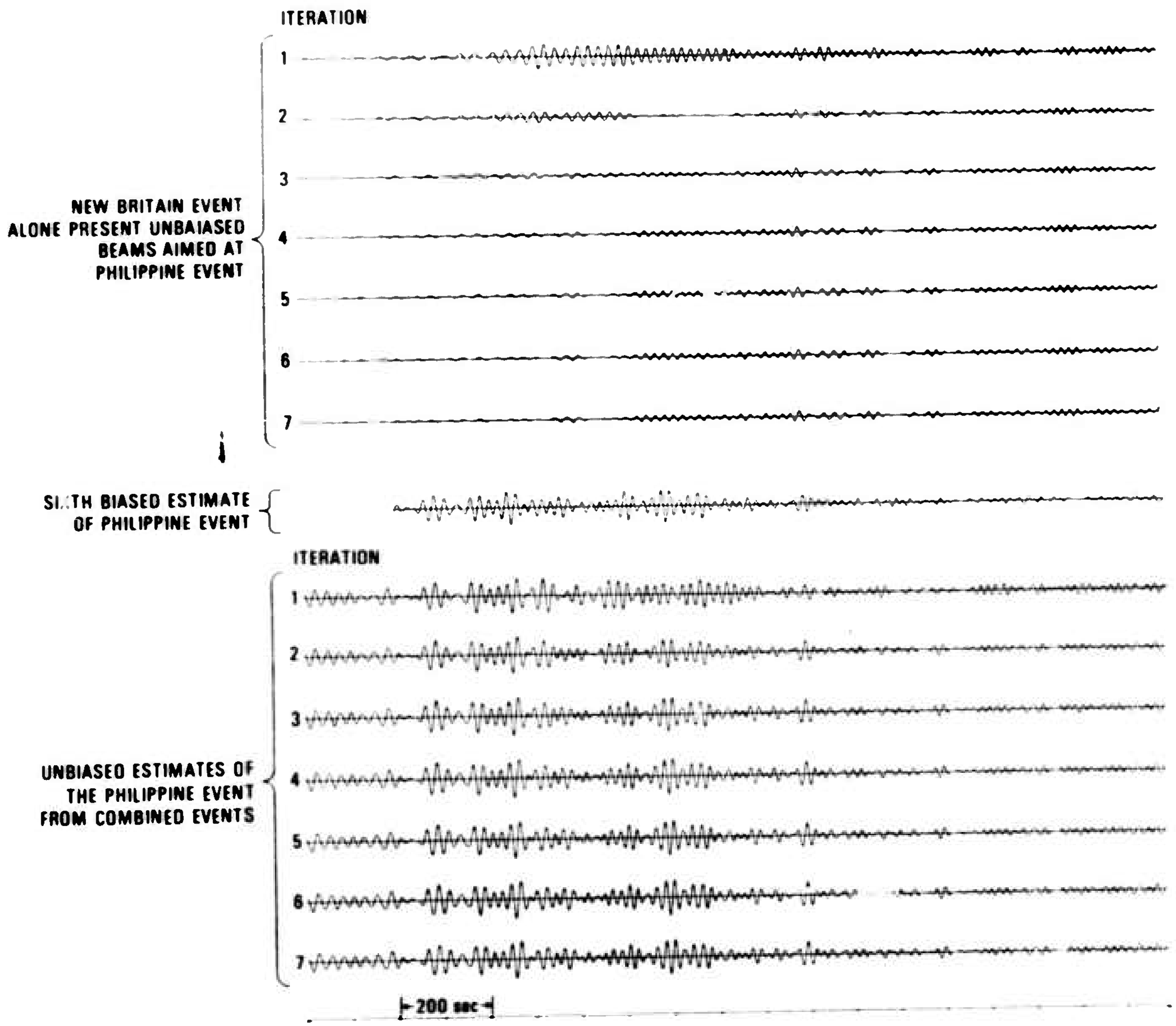

Figure 9b. Time domain analysis of the Philippine and New Britain events using the reduced LASA array. For detailed explanation see caption under Figure 8.

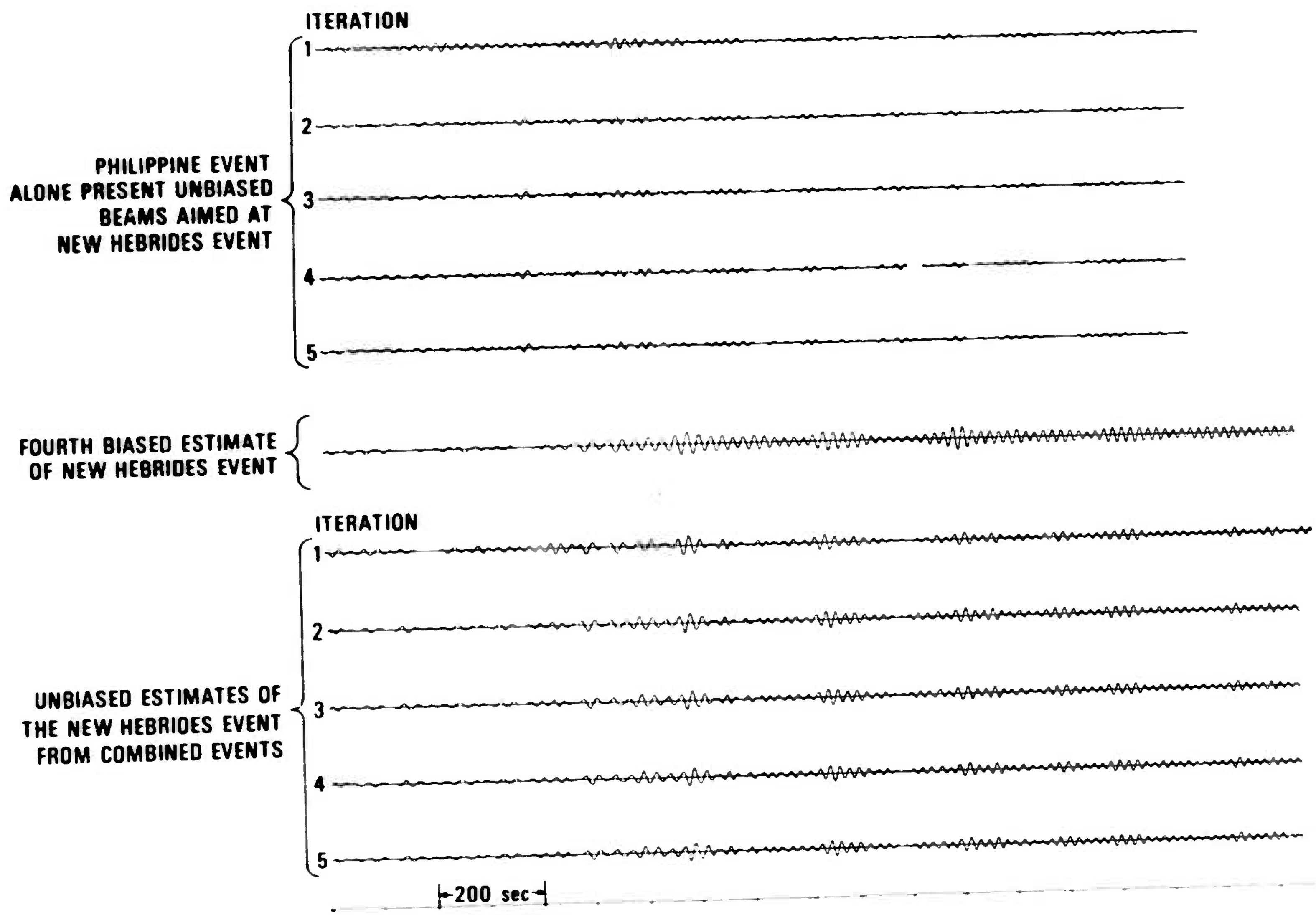

Figure 10a. Time domain analysis of the Philippine and New Hebrides events using the full LASA array. For detailed explanation see caption under Figure 8.

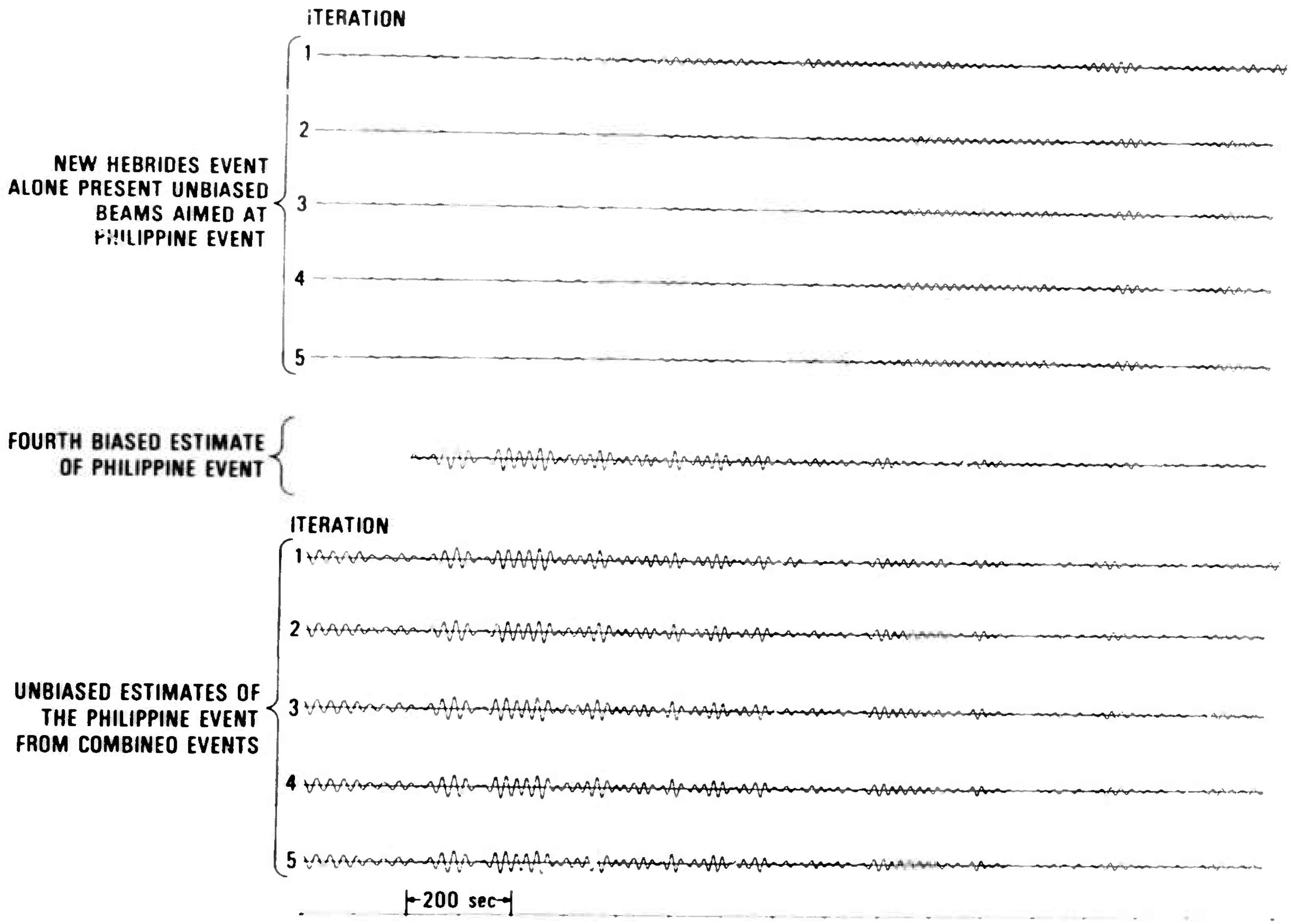

Figure 10b. Time domain analysis of the Philippine and New Hebrides events using the full LASA array. For detailed explanation see caption under Figure 8.

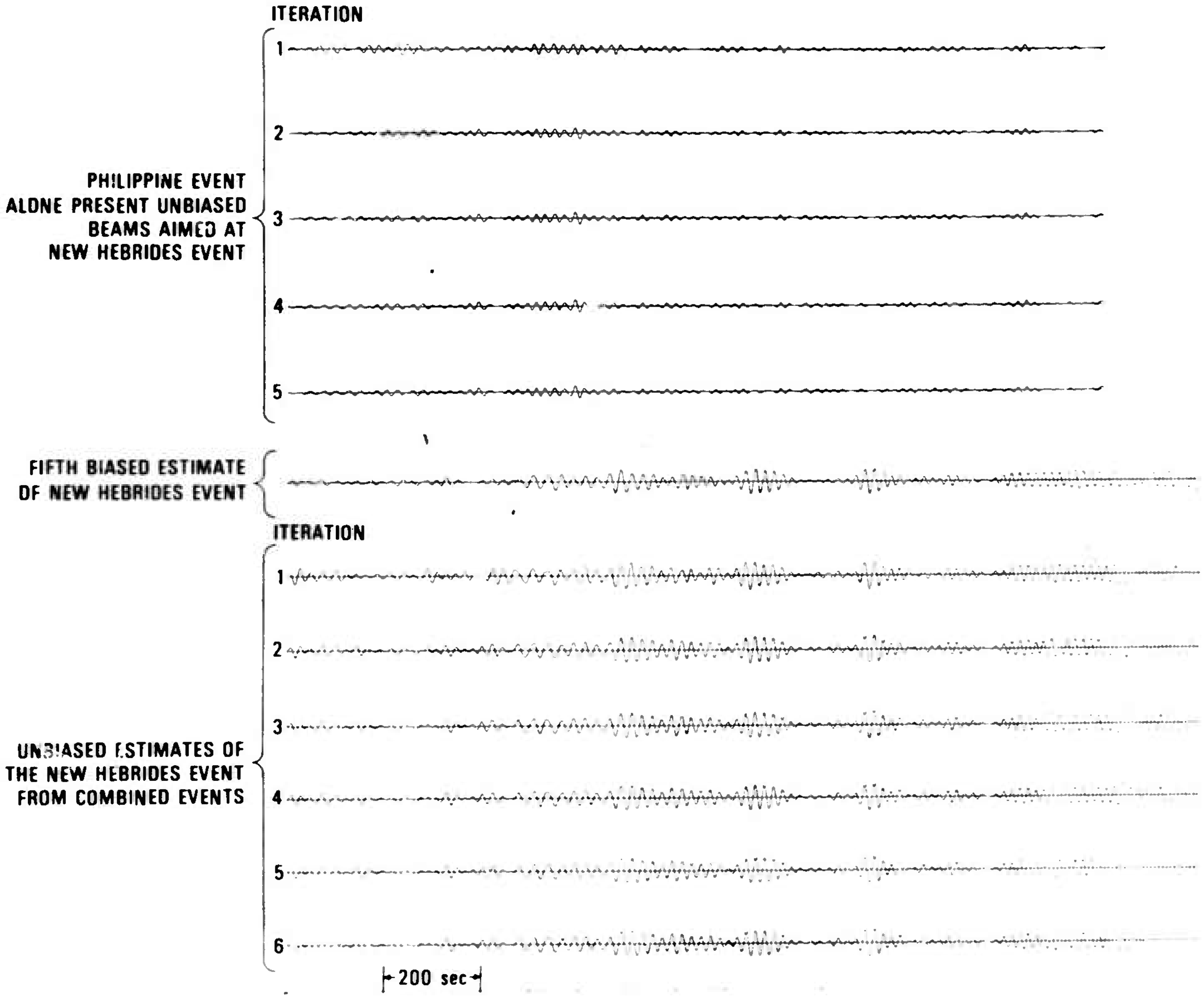

Figure 11a. Time domain analysis of the Philippine and New Hebrides events using the reduced LASA array. For detailed explanation see caption under Figure 8.

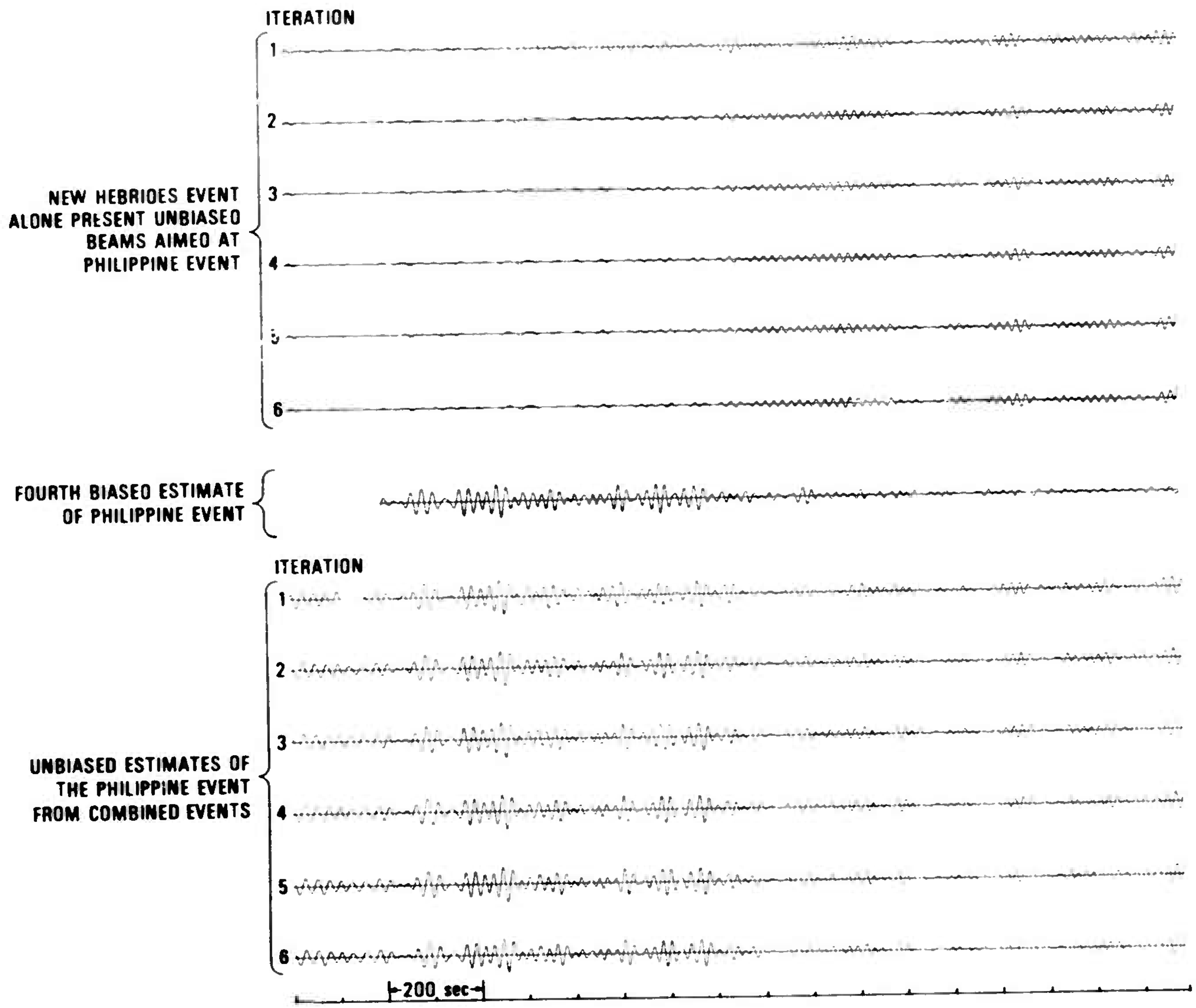

Figure 11b. Time domain analysis of the Philippine and New Hebrides events using the reduced LASA array. For detailed explanation see caption under Figure 8.

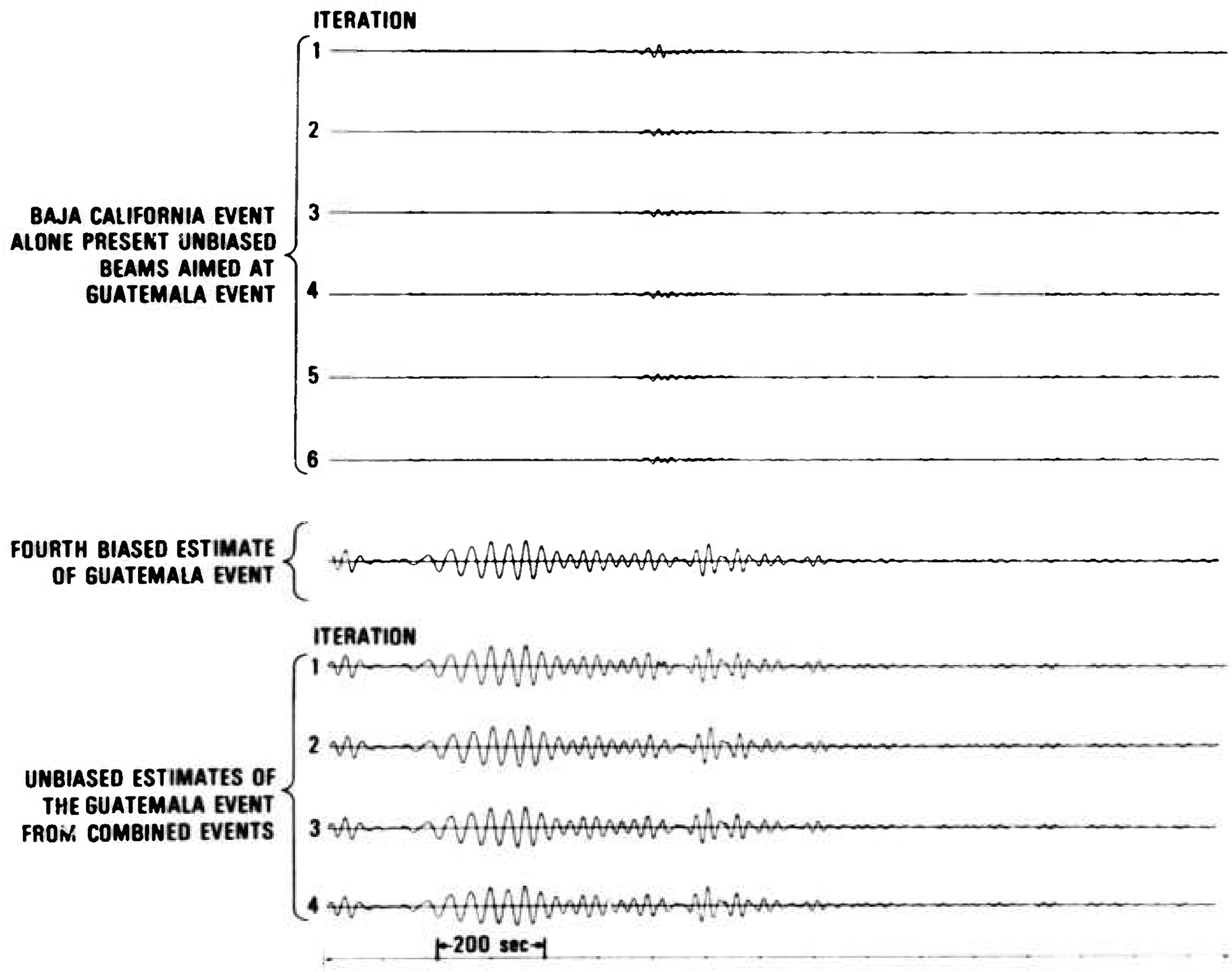

Figure 12a. Time domain analysis of Baja California and Guatemala events using the full LASA array. For detailed explanation see caption under Figure 8.

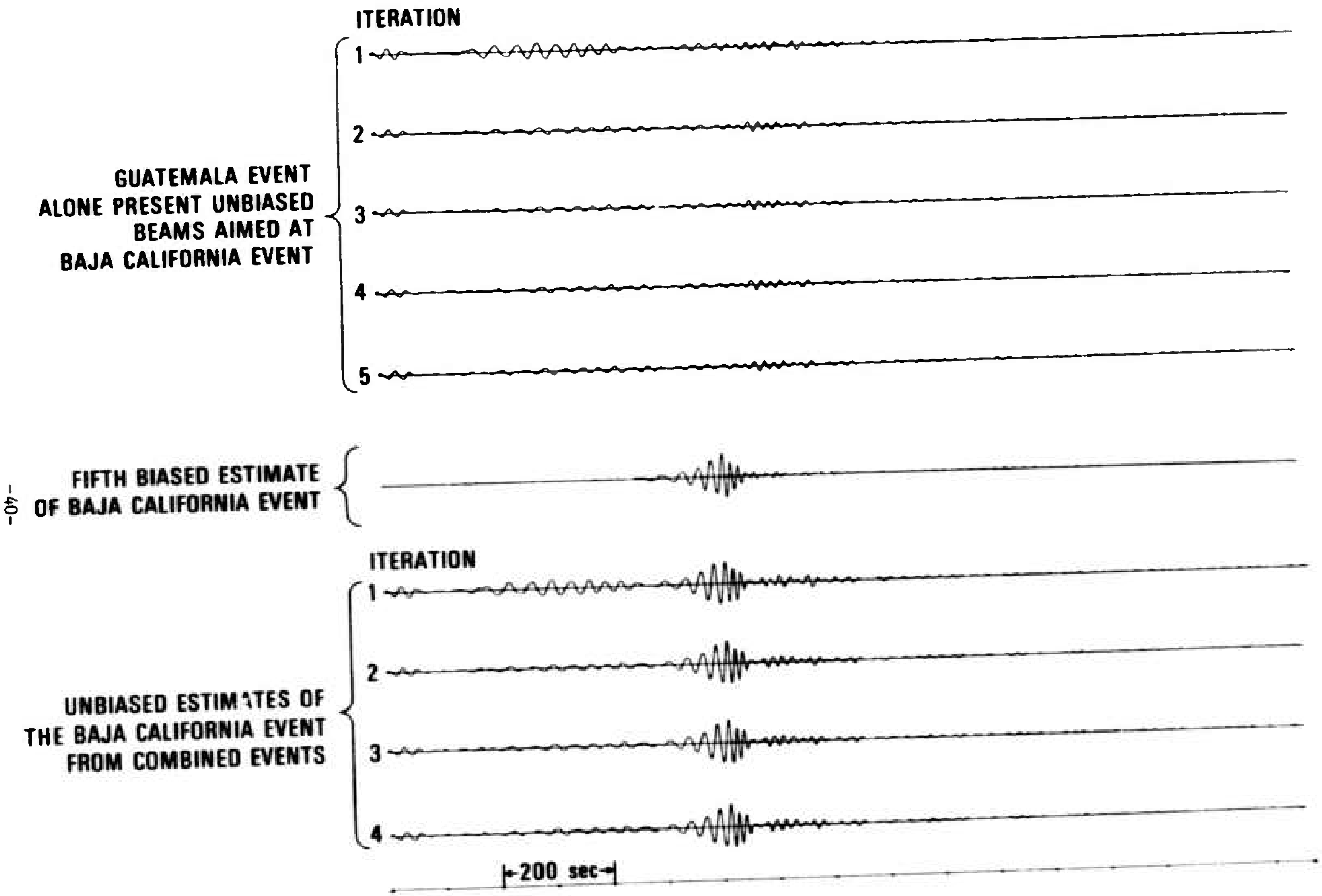

Figure 12b. Time domain analysis of Baja California and Guatemala events using the full LASA array. For detailed explanation see caption under Figure 8.

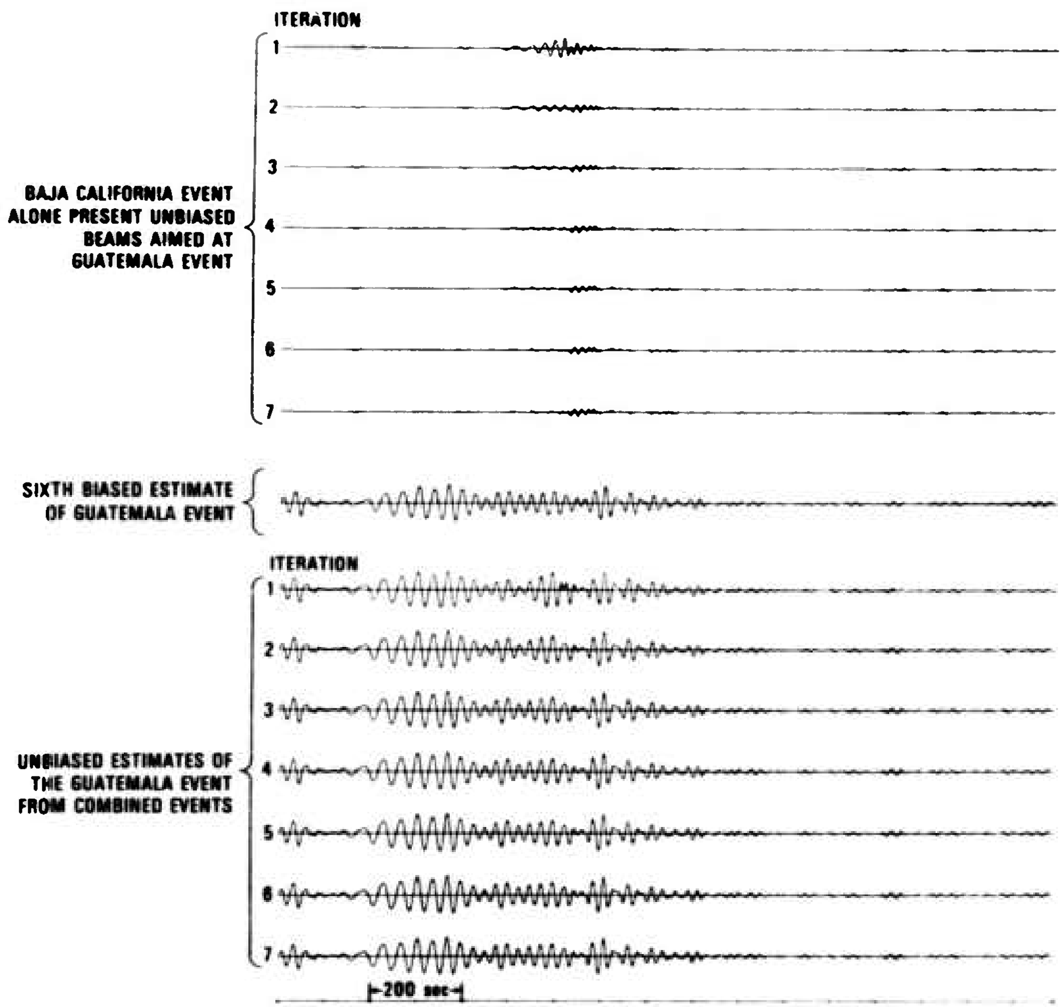

Figure 13a. Time domain analysis of the Baja California and Guatemala events using the reduced LASA array. For detailed explanation see caption under Figure 8.

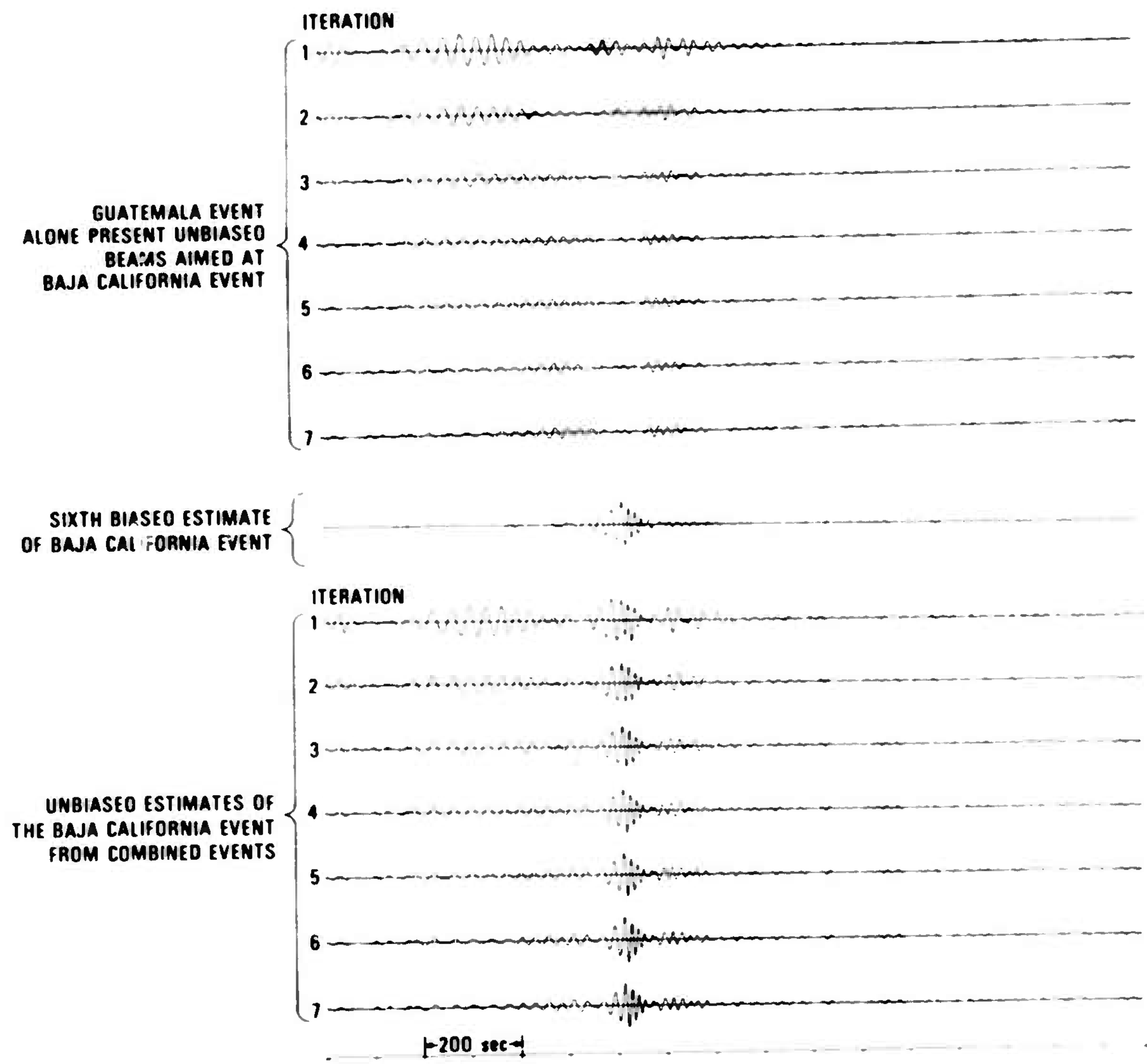

Figure 13b. Time domain analysis of the Baja California and Guatemala events using the reduced LASA array. For detailed explanation see caption under Figure 8.

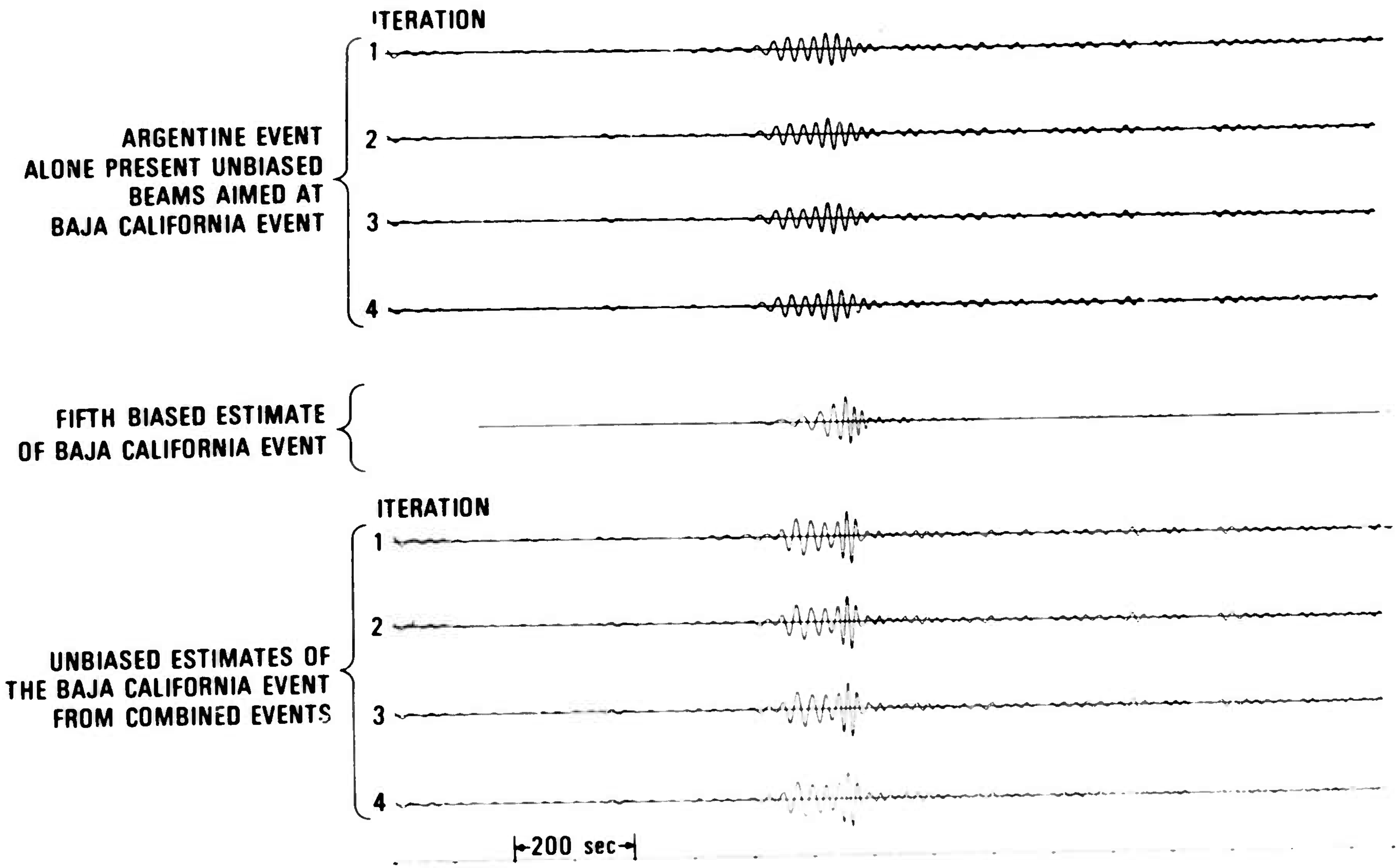

Figure 14a. Time domain analysis of the Baja California and Argentine events using the full LASA array. For detailed explanation see caption under Figure 8.

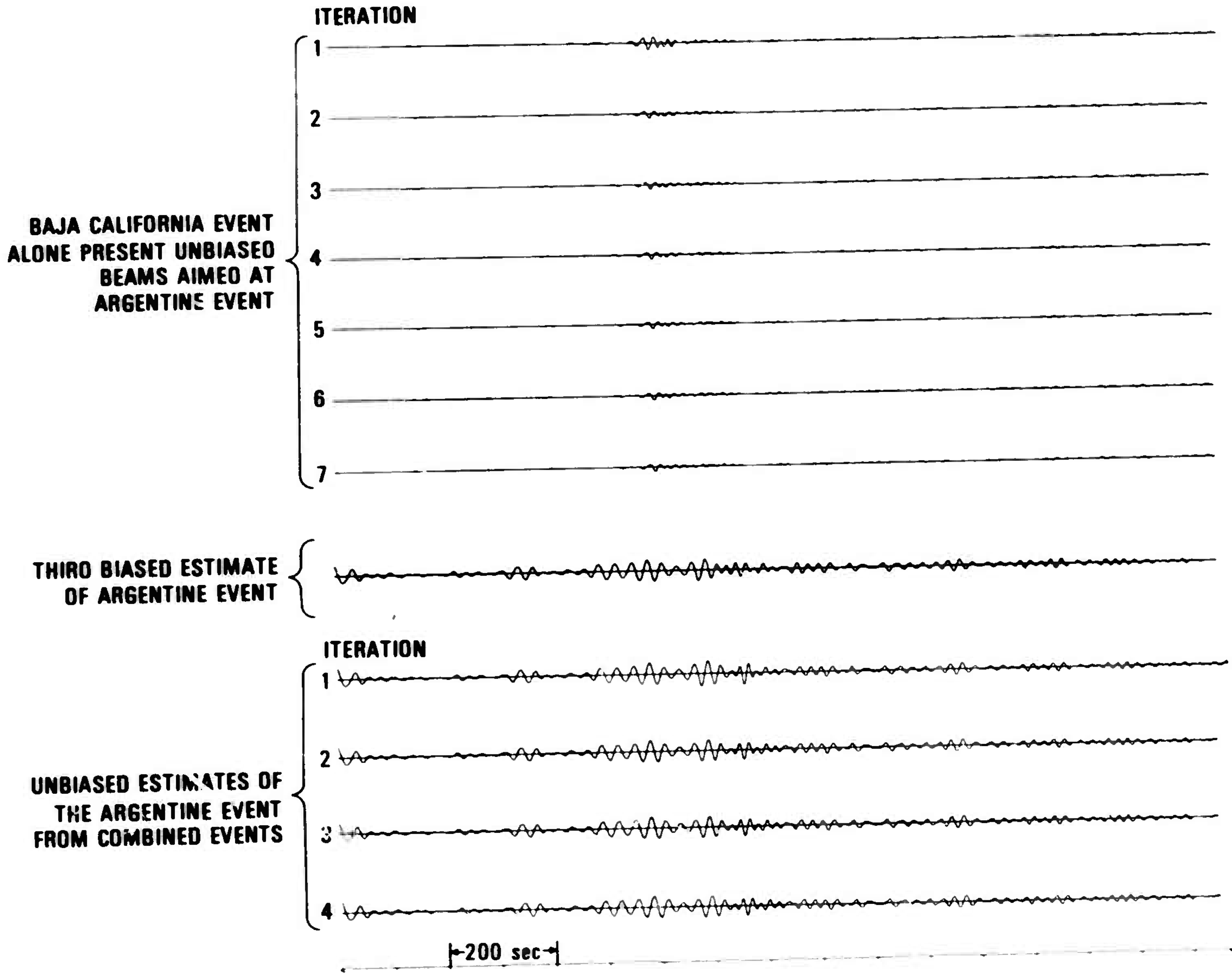

Figure 14b. Time domain analysis of the Baja California and Argentine events using the full LASA array. For detailed explanation see caption under Figure 8.

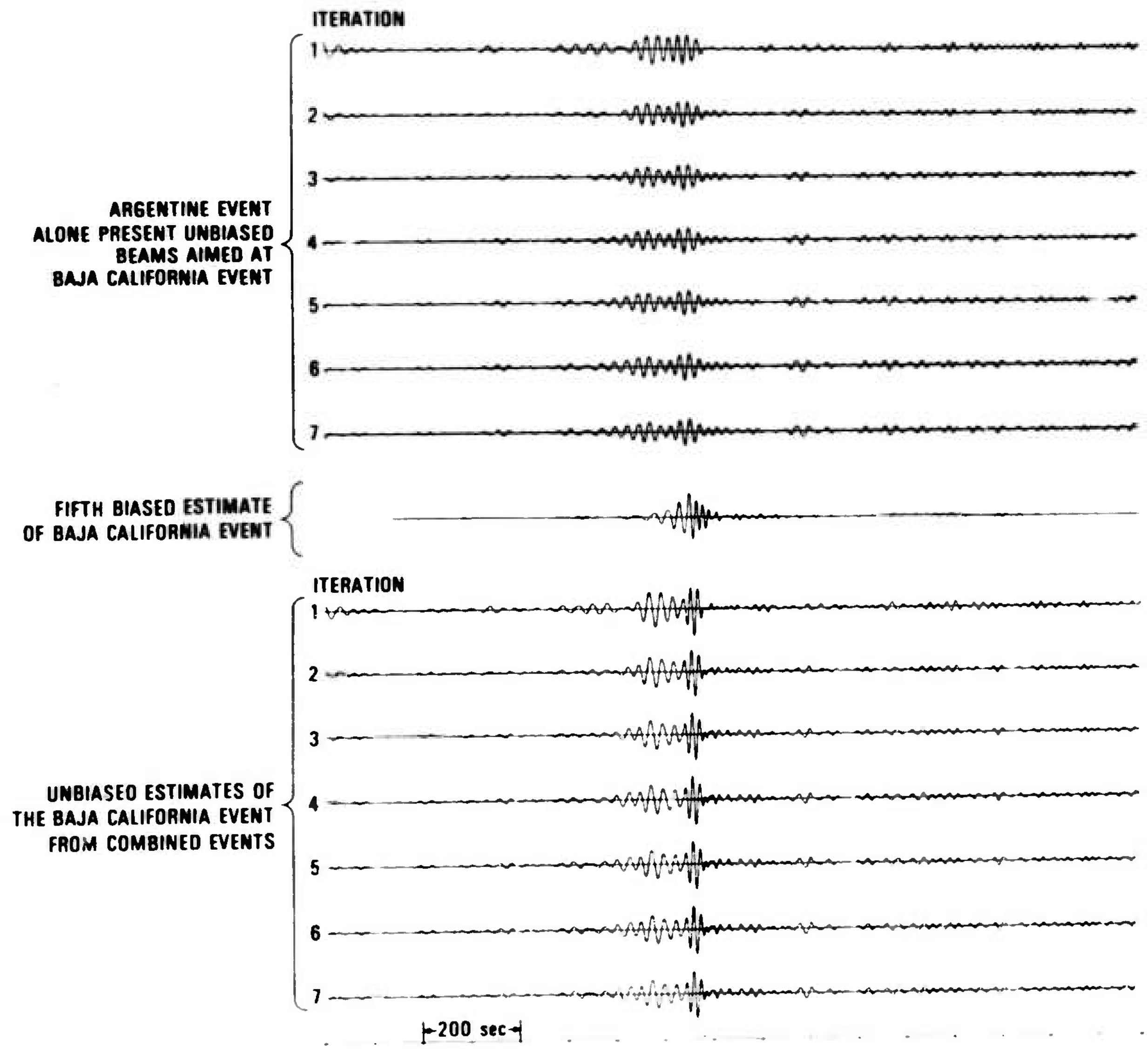

Figure 15a. Time domain analysis of the Baja California and Argentine events using the reduced LASA array. For detailed explanation see caption under Figure 8.

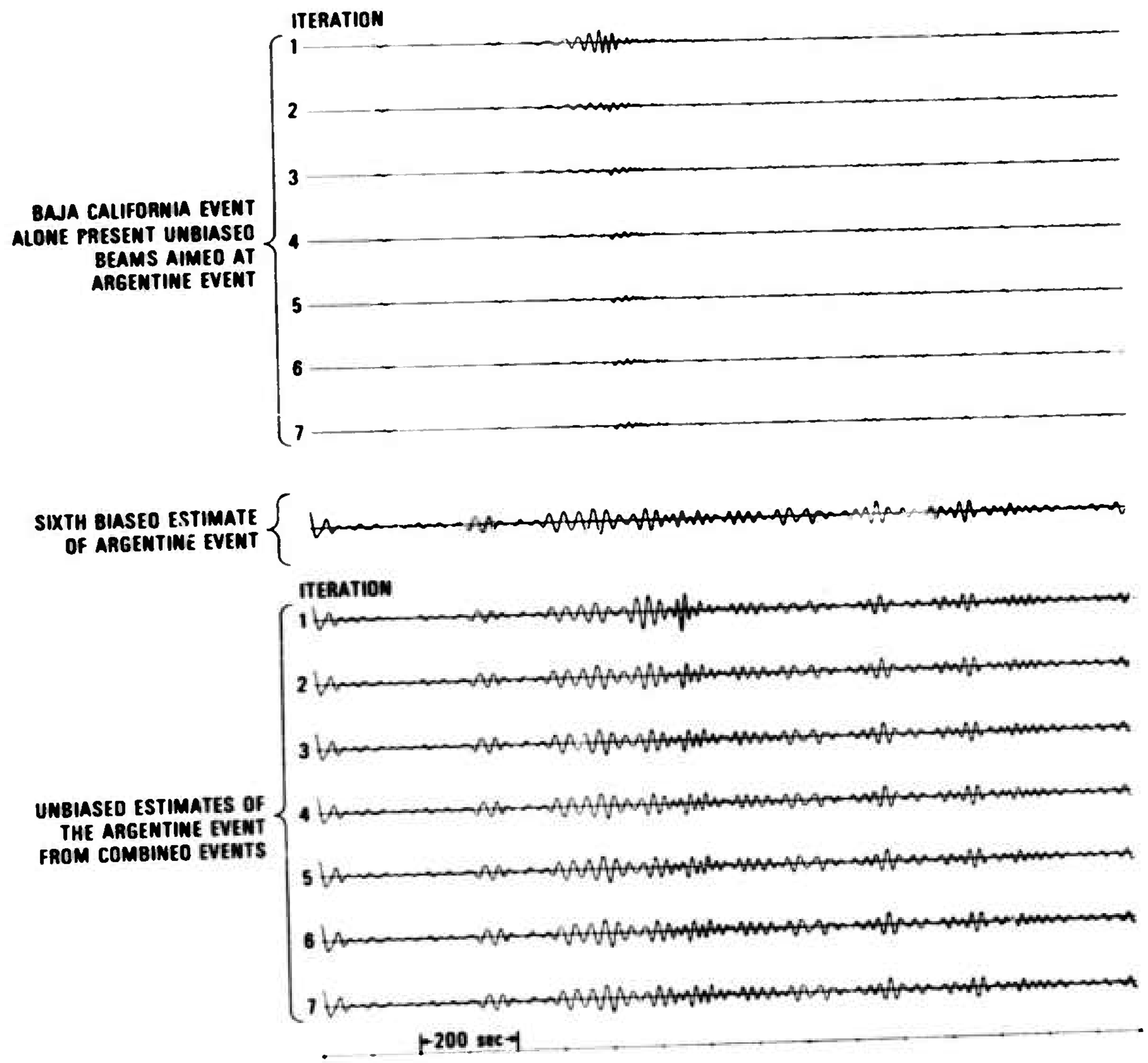

Figure 15b. Time domain analysis of the Baja California and Argentine events using the reduced LASA array. For detailed explanation see caption under Figure 8.